Drivers for Fostering Agroforestry Systems in Temperate and Mediterranean Climates: Past, Present, and Future

Franziska Wolpert

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Thesis committee:

Referee and supervisor: Prof. Dr. Tobias Plieninger

Referee: Prof. Dr. Andreas Thiel

Supervisor: Dr. Cristina Quintas-Soriano

External examiner: Prof. Dr. Claudia Bieling

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All photos, tables, and graphs are done by Franziska Wolpert unless otherwise stated.

Pictures on the title page:

The left picture shows an abandoned cherry fruit tree orchard in Wendershausen, Germany (*Streuobstwiese)*.
The picture on the right side displays a traditional oak agroforestry system in Spain *(dehesa)*

Scientific publications

This doctoral thesis is the synthesis of a compilation of the following three scientific articles.

Article I:
Wolpert, F., Quintas-Soriano, C., & Plieninger, T. (2020). Exploring land-use histories of tree-crop landscapes: a cross-site comparison in the Mediterranean Basin. *Sustainability Science*, *15*(5), 1267-1283.

Article II:
Wolpert, F., Quintas-Soriano, C., Pulido, F., Huntsinger, L., & Plieninger, T. (2022). Collaborative agroforestry to mitigate wildfires in Extremadura, Spain: land manager motivations and perceptions of outcomes, benefits, and policy needs. *Agroforestry Systems*, *96*(8), 1135-1149.

Article III:
Wolpert, F., Quintas-Soriano, C., Davison, B., & Plieninger, T. Integration of staple perennial food crops in agroforestry systems: exploring growers' motivations, aims and challenges of sweet chestnut (Castanea ssp.) in Germany. (Submitted)

In the following text, these articles are referred to as article I, article II, and article III. They are all attached in the Appendix of this thesis. The first two articles in the Appendix have been published and are presented in the published format. The third publication is under consideration by an international scientific journal and is presented in the form in which it was recently submitted.

As side activities during the process of writing my doctoral thesis, I contributed to the following book chapters. These are not referred to in the thesis.

García-Martín, M., Quintas-Soriano, C., Torralba, M., Wolpert, F., & Plieninger, T. (2021). Landscape change in Europe. In Weith, T., Barkmann, T., Gaasch, N., Rogga, S., Strauß, C., Zscheischler, J. (eds) *Sustainable Land Management in a European Context* (pp. 17-37). Springer, Cham.

Torralba, M., García-Martín, M., Quintas-Soriano, C., Wolpert, F., & Plieninger, T. (2019). Implementation of social-ecological management approaches in biosphere reserves in the Mediterranean Basin. In Reed, M.G. & Price M.F. (eds) *UNESCO Biosphere Reserves. Supporting Biocultural Diversity, Sustainability and Society* (pp. 281-296). Routledge, Abingdon, Oxon; New York, NY

Abstract

Traditional multifunctional agroforestry landscapes provide not only food but also support biodiversity and provide a multitude of ecosystem services. However, such landscapes have been frequently lost in the last decades. Given the multiple global challenges that have emerged from an industrial model of agriculture, agroforestry as a concept based on multifunctionality is increasingly regarded as key for sustainable food production systems of the future. To guide future land management and policies, past land-use change histories as well as the motivations and challenges of current land managers have to be understood and considered.

Three articles covering different spatial and temporal scales are the basis of this thesis. In the first article, I conducted a literature review and compiled landscape histories over 200 years of nine tree crop landscapes in eight different countries of the Mediterranean Basin. I found an accelerating change of landscape processes mostly steered towards abandonment or intensification by different interrelated driving forces, including socio-cultural, economic, political, technical, and natural drivers. Recently, a process that I called renaissance occurred in two landscapes and raises hope for a new appreciation of such multifunctional landscapes. In the second and third articles, I studied the present challenges and motivations of land-managers by conducting social surveys. I asked them about their perceptions of social-ecological outcomes of agroforestry land management systems and about successful measures for fostering agroforestry. In article II, I chose the adjacent counties Sierra de Gata and Las Hurdes in Spain as case study sites to interview members of an Integrated Landscape Initiative called *Mosaico.* These farmers collaborate in managing agroforestry systems for mitigating wildfires. Article III covered chestnut fruit cultivation in Germany as a case study of adopting a new potentially profitable crop to agroforestry systems. Here, I wanted to assess the motivations and challenges of the people that already cultivate that tree crop. In my second and third articles, I found that both farmers from the Integrated Landscape Initiative and the chestnut growers were highly motivated. Chestnut growers, especially junior growers, showed the highest motivation regarding sustainable land management. Combatting depopulation was the highest motivation for farmers of the landscape initiative. Generally, I found the neo-rural playing an underestimated and important role in the initiative, as they were especially motivated by practices increasing biodiversity and enhancing well-being. Barriers were in both cases unsuitable legislation regarding perennial crops and agroforestry as well as low funding opportunities for multifunctional systems. Besides the perceived effectiveness of wildfire mitigation in Spain, I found diverse further positive personal and regional outcomes due to collaborative agroforestry. Similarly, chestnut growers perceived tree crops as providing multiple positive ecosystem services. The barriers that the farmers face and the motivations and success factors they highlighted could help guiding land management decisions.

The results of all three articles are discussed and synthesized in a compiled story, covering the past, and present, and future, including perspectives land management and its policies in the field of agroforestry. This thesis covers case studies in temperate and Mediterranean climates. The insights have to be adapted to local contexts and thus, can be transferred to other climates with similar land change patterns.

Keywords: tree crop landscape, drivers of change, collaborative agroforestry, wildfire mitigation, neo-rurals, perennial staple food, chestnuts

Zusammenfassung (German abstract)

Traditionelle multifunktionale Agroforst-Landschaften liefern nicht nur Nahrungsmittel, sondern fördern auch die biologische Vielfalt und eine Vielzahl weiterer Ökosystemleistungen. Solche Landschaften sind jedoch im Laufe der letzten Jahrzehnte durch Landschaftswandel gefährdet worden. Angesichts der vielfältigen globalen Herausforderungen, die durch die industrielle Landwirtschaft entstanden sind, wird die Agroforstwirtschaft zunehmend als Schlüssel für nachhaltige Lebensmittelproduktionssysteme der Zukunft angesehen. Um die politische Gestaltung der zukünftigen Landbewirtschaftung zu lenken, müssen sowohl der Landnutzungswandel der Vergangenheit als auch die Motivationen und Herausforderungen der derzeitigen LandwirtInnen verstanden und berücksichtigt werden.

Drei wissenschaftliche Artikel, die unterschiedliche räumliche und zeitliche Dimensionen abdecken, bilden die Grundlage für diese Arbeit. Die erste Veröffentlichung umfasst eine Literaturstudie zur 200-jährigen Landschaftsgeschichte von neun Baum-Kulturlandschaften in acht verschiedenen Ländern des Mittelmeerraums. Dabei wurde ein sich beschleunigender Wandel der Landschaftsprozesse festgestellt, der im letzten Jahrhundert vor allem von der Aufgabe oder Intensivierung der Landnutzung geprägt war. Er ist auf verschiedene miteinander verknüpfte Triebkräfte zurückzuführen; darunter soziokulturelle, wirtschaftliche, politische, technische und natürliche. In jüngster Zeit ist in zwei Landschaften ein Prozess eingetreten, der als Renaissance bezeichnet werden kann und Hoffnung auf eine neue Wertschätzung solcher multifunktionalen Landschaften gibt.

In der zweiten und dritten Veröffentlichung werden mittels Interviews die gegenwärtigen Herausforderungen und Motivationen von LandbewirtschafterInnen untersucht. In dem zweiten Artikel dienten die angrenzenden Landkreise Sierra de Gata und Las Hurdes im Westen Spaniens als Modellregion um MitgliederInnen der Landschaftsinitiative *Mosaico* zu befragen. Diese LandwirtInnen kooperieren, um gemeinsam durch das Bewirtschaften von Agroforstsystemen zur Minderung der Waldbrandgefahr beizutragen. Veröffentlichung III befasst sich mit dem Esskastanienanbau in Deutschland als Fallstudie für die Einführung einer neuen, potenziell rentablen mehrjährigen Kulturpflanze in Agroforstsystemen. Sowohl die LandwirtInnen der Landschaftsinitiative in Spanien als auch die KastanienanbauerInnen in Deutschland waren hoch motiviert. Die KastanienanbauerInnen, insbesondere die jüngeren, zeigten die höchste Motivation für nachhaltige Landbewirtschaftung. Der Kampf gegen Landflucht war die größte Motivation für die LandwirtInnen der Landschaftsinitiative *Mosaico*. Generell stellte ich fest, dass die Neu-LandwirtInnen (Neo-rurals) eine unterschätzte und wichtige Rolle in der Landschaftsinitiative spielen, vor allem angetrieben durch den Wunsch nach mehr biologischer Vielfalt und der Steigerung des persönlichen Wohlbefindens. Hindernisse waren in beiden Fällen ungeeignete Rechtsvorschriften für mehrjährige Kulturen/Agroforstwirtschaft sowie eine unzureichende Finanzierung multifunktionaler Systeme. Neben der wahrgenommenen Effektivität der Waldbrandbekämpfung in Spanien wurden weitere positive persönliche und regionale Auswirkungen der gemeinschaftlichen Agroforstwirtschaft festgestellt. In ähnlicher Weise brachten die KastanienanbauerInnen eine Vielzahl positiver Ökosystemleistungen mit den Baumkulturen in Verbindung.

Die Erkenntnisse über Herausforderungen, mit denen die LandwirtInnen konfrontiert sind, sowie die von ihnen hervorgehobenen Motivationen und Erfolgsfaktoren können LandwirtInnen und PolitikerInnen dabei helfen, einen Einblick in die Komplexität der Lage zu erlangen und lokal

angepasste Lösungen für eine zukunftsfähige Landwirtschaft zu finden. Die Ergebnisse aller drei Veröffentlichungen werden in der vorliegenden Arbeit zusammengefasst und diskutiert. Sie decken sowohl Vergangenheit und Gegenwart ab, als auch Perspektiven für eine künftige Landbewirtschaftung und Politik im Bereich der Agroforstwirtschaft. Es werden Fallstudien in gemäßigtem und mediterranem Klima behandelt. Die Maßnahmen sollten immer an die lokalen Gegebenheiten angepasst werden und können so auch auf andere Klimazonen übertragen werden, in denen ähnliche Muster des Landschaftswandels auftreten.

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1. Introduction

Traditional food production landscapes are complex social-ecological systems shaped by humans, and land management has been an integral part of the diversity of such landscapes (Martín-López et al. 2016). Worldwide, trees and shrubs have been part of or have even dominated these landscapes (Kreitzman et al. 2020). In the Early Mesolithic (9600–7000/6500 BP), hazelnuts used to be a major component of the human diet in Central Europe (Holst 2010). In Kyrgyzstan, walnut (see Figure 1), as well as diverse fruit forests have been the basis of livelihoods, and these forests have been maintained by humans for millennia if they were not even created by humans in the first place (Beer et al. 2008; Sakbaeva et al. 2013). Acorns used to be a traditional staple food crop not only in Europe but also in Asia and North America (Bainbridge 1986). In the Mediterranean Basin, chestnut and olive trees are examples of tree fruits that have served as staple food crops for centuries (Infante-Amate and Molina 2013; Tagliaferri and Di Lonardo 2016). In Germany, traditional tree crop landscapes are multispecies fruit orchard meadows, also known as *Streuobstwiesen* (Plieninger et al. 2015).

Figure 1: Walnut forest in Kyrgyzstan. The photo was taken by Halis Duran CC BY-SA 3.0.

The culture of the people living and working on the land is closely linked to these tree crops (Infante-Amate and Molina 2013). Tree crop landscapes have provided a wide range of food through the mosaic of different management intensities and crop diversity, and at the same time upheld landscape sustainability and high levels of biodiversity (Blondel et al. 2010). Traditional tree crop landscapes are known as biodiversity hotspots (UNEP/MAP 2016), and biodiversity is the basis for the provision of most ecosystem services (Ikerd 1993). Ecosystem services are benefits that can be received from ecosystems and comprise provisioning, regulating, cultural, and supporting services. For example, provisioning services contain food, wood, and genetic resources (MEA 2013). Due to their complexity and high biodiversity, tree crop landscapes do not only supply multiple provisioning services, but also manifold other ecosystem services, such as regulation of water cycles and climate regulation (IPCC

2019; Schwarzer 2021), as well as cultural services including recreational and spiritual value (Oteros-Rozas et al. 2018).

Currently, there is a polarisation of land-use in many parts of Europe: Land-use intensification is prevalent on more favorable sites and land abandonment in marginal areas (Plieninger et al. 2006). Intensification implies that labor as well as off-farm inputs are increased to enhance yield. Abandonment and intensification of multifunctional landscapes both tend to lead to a loss of biodiversity, as an intermediate state of disturbance harbors the highest biodiversity (Uchida and Ushimaru 2014). Loss of biodiversity leads to the degradation of ecosystem services as these are interdependent (Isbell et al. 2015). Low ecosystem services supply negatively affects human well-being, as, for example, a material minimum for a good life is not available or health is negatively affected by an unbalanced diet (MEA 2003). Human well-being and drivers of change affect each other. For example, an economic crisis (economic driver) can affect human health, which in turn negatively affects the economy as sick people are working less (Walker 2010). These drivers have a direct impact on ecosystem services, as, for example, profitability of a special crop can negatively affect biodiversity through intensification (van Vliet et al. 2015). The described feedback loop is depicted in Figure 2. The reality, however, is much more complex, for example, economic growth that is based on the intensification of land-use systems has not only negative short-term effects, but unsustainable land-use also has negative long-term effects on poorer groups through environmental degradation (Mace et al. 2018).

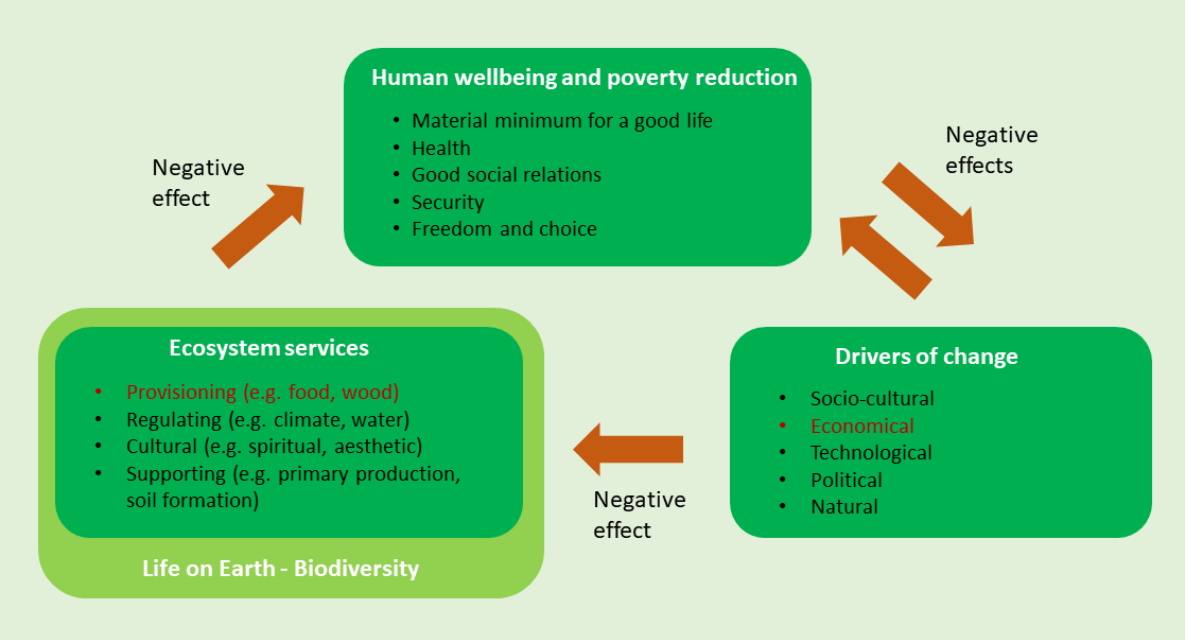

Figure 2: Framework on the relation of ecosystem services, human well-being, and drivers of change. The direction of impact is shown by brown arrows. Provisioning services and economical drivers are marked red as a general focus on provisioning services supported by economical drivers foster a negative feedback loop. The figure was adapted from Iniesta-Arandia et al. (2014).

According to the Eat-Lancet commission, the current global food system is the single largest driver of ecosystem degradation and transgression of planetary boundaries (Willett et al. 2019). Two examples are biodiversity loss and climate change. Globally, annual species extinction rates have increased by 100-1000 times since the beginning of the Anthropocene, and they are expected to increase about 10-fold in the current century, with land-use change being one of the major drivers (Rockström et al. 2009). Climate change is boosted by agriculture not only through greenhouse gas emissions (Tubiello et al. 2013) but also through the decreased cooling effect of a reduced vegetation cover (Schwarzer

2021). Due to unsustainable agricultural production systems, future global food security is at risk. The conclusion of leading scientists is clear: A comprehensive food system transformation is needed (Willett et al. 2019).

In the last decades, agroforestry has increasingly been seen as a tool to decrease the negative impacts of food production and to enhance ecosystem provision on agricultural land (Torralba et al. 2016). Agroforestry combines trees and shrubs with either annual agriculture (silvoarable) or grassland (silvopastoral). Such a combination provides synergies through the integration of different components. The tree crop systems, like the walnut forests described above, are examples of traditional agroforestry systems including food production from perennial staple food crops. Most modern agroforestry systems are designed as alley cropping systems, a stripe-type integration of trees or shrubs. The perennial component often consists of energy fuel crops (mainly poplar or willow) or trees grown for quality wood and is combined with annual agricultural systems (Nerlich et al. 2013). The integration of tree crops, especially tree nuts, in annual agricultural systems and pasture has a high potential for sustainable food production and is highly underappreciated (Kreitzman et al. 2020). Agroforestry systems can have diverse designs and management intensities, and therefore ecosystem and human well-being outcomes also differ. However, the integration of a perennial component is associated with multiple positive outcomes on biodiversity and ecosystem services categories as described above (Kreitzman et al. 2022; Veldkamp et al. 2023).

Despite the many benefits in terms of ecosystem and human well-being outcomes, there is an ongoing intensification and abandonment of traditional agroforestry systems. To develop strategies for reversing this trend, a thorough understanding of the historic processes of traditional agroforestry landscapes is needed (Antrop 2005). Knowledge about the complex driving forces that have shaped the history of such agroforestry landscapes is of special interest for informing sustainable land management but remains rarely covered in the scientific literature (Plieninger et al. 2016). There is a research gap in the comparison of landscape histories of tree crop landscape s across different sites, as well as the driving forces of landscape change covering longer time frames (Frattaroli et al. 2014; Jepsen et al. 2015).

The slow adoption of modern agroforestry systems and rare revitalization of traditional systems implies that barriers are hampering this. To guide future decision making it is necessary to understand those barriers, and how agroforestry with its multiple values of ecosystem services can be fostered in its implementation as well as management (Black et al. 1998; Antrop 2005). As motivations are defined as an energizing force that drives action (Parks and Guay 2009), farmers´ motivation to manage their land is of interest as well, as it will form future landscapes.

In this thesis, I aimed to investigate the motivations and barriers of pioneers that cultivate agroforestry systems. I found an Integrated Landscape Initiative that collaboratively manages agroforestry systems to mitigate wildfires. Collective engagement in wildfire mitigation is currently recognized as useful in complementing suppression measures and has been studied with different foci (Otero et al. 2018; Górriz-Mifsud et al. 2019; Palaiologou et al. 2020). However, little is known about the motivations and barriers of farmers collaboratively managing agroforestry systems and about the personal and regional outcomes of such management.

A further approach, to revitalizing traditional and implementing modern agroforestry systems that I identified, is the integration of innovative tree crops in supporting the profitability of a system. Especially, trees providing staple food crops, like chestnuts, can play an important role in future food production, and at the same time provide beneficial environmental outcomes (Davison et al. 2021). Although chestnuts are increasingly cultivated in temperate zones of Europe, little is known about the chestnut growers´ motivations and barriers and what measures would help scale up chestnut production in Germany.

These topics and identified research gaps formed the objectives of my thesis that will be covered in the following chapter.

2. Objectives and Structure

The main objectives of this thesis are to understand how land-use has changed from traditionally diverse agroforestry systems to simple annual systems, as well as to explore current motivations and barriers of land managers to find possible ways to maintain and revitalize such diverse land-use systems in order to inform sustainable land management.

Specific objectives are the basis of the three manuscripts that my thesis includes. These are:

- To explore the history of tree crop landscapes in the Mediterranean basin regarding their common and diverging patterns of land-use change (article I)
- To investigate the social-ecological characteristics of an Integrated Landscape Initiative that seeks to reduce wildfire impacts through agroforestry (article II)
- To assess the status quo of chestnut cultivation in Germany as a case study of perennial staple food crop integration in agroforestry systems (article III)

Following these objectives, I covered different temporal and spatial scales, namely past, present, and future as well as regional, national, and ecozone scales (Figure 3). In my first article, I focused on the past to review land-use histories in the Mediterranean, on an ecozone scale. I derived common patterns of driving forces, which transformed these social-ecological systems in order to understand the possible valorization of the multiple societal values that tree crop landscapes comprise. For the second and third article, I was interested in the motivations of people managing agroforestry systems and how these systems can be put into value. In case of article II, I chose a present, regional case study of a farmer initiative called *Mosaico*. The aim of the initiative is to reduce wildfire threats through the collaborative management of agroforestry systems. In my third article, I considered a national scale. I aimed to examine chestnut cultivation in Germany, as chestnut growers in Germany have not been investigated before, and chestnut trees seem to be an interesting and present case for covering perennial staple food crop integration in agroforestry systems. All three studies are conducted in order to inform future land management and policies.

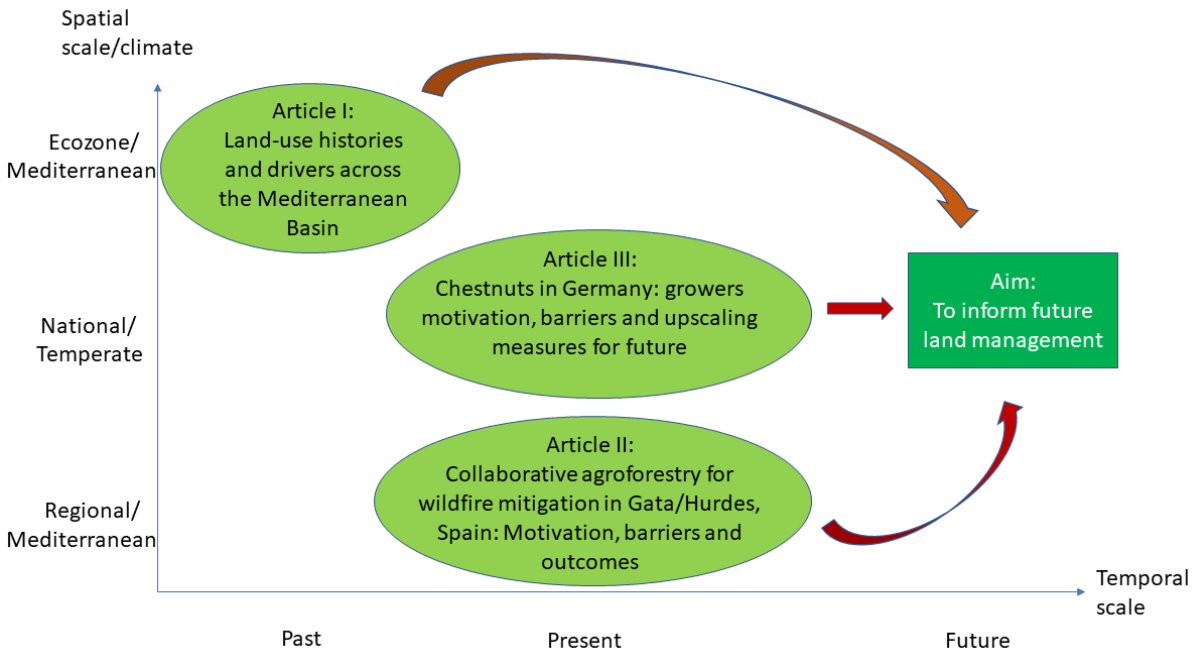

Figure 3: Structure of the doctoral thesis, classifying the three articles across temporal and spatial scales.

In each of the articles, I followed the objectives described above, formulating several subsequent research objectives:

Article I	(1) describe the dominant land-use change processes across three tree crop types, namely cork oak, chestnut, and olives, using three exemplary sites per crop (2) identify and classify the main drivers that determine these landscapes' land change histories.
Article II	(1) explore motivations and barriers of an Integrated Landscape Initiative´s participants (2) get insights into perceived initiative outcomes and success factors (3) reveal differences between rural and neo-rural participants
Article III	(1) explore the characteristics of chestnut stands and their management in Germany (2) evaluate the main motivations, aims, and challenges of chestnut growers regarding chestnut cultivation (3) identify measures for upscaling chestnut production in Germany (4) explore differences between junior and senior chestnut growers

3. Methodological Approaches and Data Analysis

Landscapes are complex social-ecological systems, and researching landscapes thus requires a holistic view (Angelstam et al. 2013). The conceptual framework behind the thesis is the ecosystem services and human well-being framework by Iniesta-Arandia et al. (2014) as described above, and the starting points for my three articles are displayed in the following graph (Figure 4).

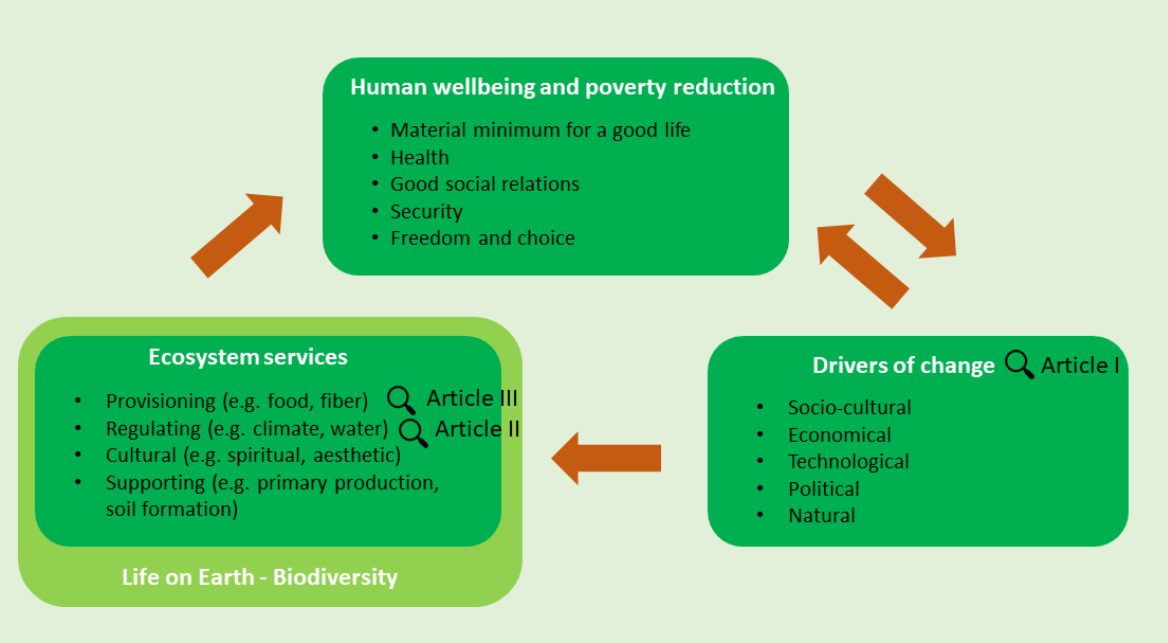

Figure 4: Ecosystem services and human well-being framework adapted from Iniesta-Arandia et al. (2014). It shows the starting points for my three articles (loupes). Article I examines the drivers of change, while article II covers regulating services (wildfire mitigation) as a way to valorize agroforestry systems. In article III, I choose a case study on a potentially profitable crop that could be integrated into modern agroforestry systems, covering provisioning services.

For all three articles, I chose a case study approach aiming for holistic insights in a complex field (Brown 2008). The approach allows in-depth, multi-faceted explorations of complex issues in real-life settings. It provides the opportunity to explore the key characteristics, meanings, and implications of the topic (Crowe et al. 2011). The three articles all have an exploratory character and cover multiple social-ecological dimensions. An overview of data elicitation and analysis of the different articles is given in Table 1. The next chapter will cover the data elicitation method and analysis of the first article. This is followed by the data elicitation method of articles II and III, and then the data analysis of articles II and III, as I employed the same approach in both articles.

Table 1: Study character, specific aims, data elicitation, and data analysis across the three articles forming this thesis.

Article	Study area	Method of data elicitation	Data analysis
I	Nine selected tree crop landscapes across the Mediterranean Basin	Literature review to conduct landscape history narratives	Extraction and systematic categorization of landscape processes and driving forces of change
II	Sierra de Gata and Las Hurdes, Spain	Structured interviews with land managers	Frequency analysis and nonparametric statistical comparison analysis
III	Germany	Structured interviews with chestnut growers	Frequency analysis and nonparametric statistical comparison analysis

3.1. Literature Review: Landscape Processes and Driving Forces

In article I, I chose a literature review approach for nine selected tree crop landscapes, covering three different tree crops, namely cork oak, chestnut, and olive. For each of the nine landscapes, I selected four to six key papers. The borders of the landscapes were defined in accordance to the reviewed studies. These key papers were the basis for compiling histories for each landscape over the last 200 years, which is a period with relatively good data availability. As there was less useful literature for the southern Mediterranean countries, I complemented the reviewed studies by conducting expert interviews for the olive landscape in Morocco, the cork oak landscape in Tunisia, and the chestnut landscape in Turkey. In a systematic approach, I identified landscape changes and classified them into processes. I defined a landscape process as a period in which the tree landscape undergoes a certain predominant process regarding the tree crop. For example, if the area of the chestnut landscape increased in France in a certain period, the related landscape process was called expansion. The landscape processes were then illustrated in a timeline to reveal common patterns and differences across tree crop landscapes.

With the help of the driving forces framework (short: drivers), I extracted the reasons behind the change of processes following the approach of Bürgi et al. (2004). A driver is defined as a human-induced or natural factor that causes a change in an ecosystem (MEA 2003). Although the processes took place mainly on the landscape scale, drivers at local to global scales were also considered. The driving forces were categorized into socio-cultural, technical, political, economic, and natural drivers (modified from Bürgi et al. 2004). The proportional contribution for each category of driving forces was then calculated for six landscape processes across all landscape histories. For example, I considered all abandonment processes and calculated the relative proportion of natural driving forces compared to other driving forces categories. This helped to reveal patterns of driving forces in connection to the processes. Studying landscape histories is a fruitful way of getting a holistic view of complex nexuses and is important for an understanding of prerequisites for a transformation towards sustainability (Angelstam et al. 2013).

3.2. Interviews

Due to the exploratory character of my research, interviews are an appropriate method which I used for the articles II and III. They are well suited to get in-depth insights into people´s points of view and motivations and can reflect complex issues (Bernard 2018). A social survey was the basis of the data for articles II and III. For both articles, I developed questions and predefined answers after detailed discussions with experts in the region, with whom I also conducted a pre-test.

The questionnaire of article II sought to shed light on land manager perceptions of the Integrated Landscape Initiative. It covers seven thematic sections on (1) land managers' characteristics, (2) land managers' activities, (3) aims/motivations, (4) perceived outcomes/performance of the initiative, (5) perceived barriers to management success, (6) perceived success factors for initiative goals, and (7) perceptions of wildfires. Most questions were designed in Likert-scale format, for which each of the respondents had to indicate their level of agreement on a scale from 1 to 5 (e.g. 1=strongly disagree to 5=strongly agree, with 3 indicating neither agree nor disagree) (Joshi et al. 2015). Respondents could add their options to predefined answers (e.g. adding a motivation that was not predefined). Open-ended questions and the possibility to add own answers also helped us to explain and supplement the data where necessary.

My goal was to survey the majority of land managers that were actively engaged in the Integrated Landscape Initiative (Varela et al. 2020; Bertomeu et al. 2022). Contact information for 95 land managers fulfilling this criterion was provided by the initiative. Finally, 66 land managers were interviewed, implying a rather high response rate of 69% (García-Martín et al. 2016; Carmenta et al. 2020). Face-to-face interviews were carried out by field assistants from September to December 2020. Safety protocols for COVID-19 risk were followed, including telephone interviews if physical meetings were not possible. Informed consent was obtained.

The questionnaire of article III was designed following the structure of the research questions: Section (1) covered data on the personal background of chestnut growers, such as age and profession. I also wanted to know if chestnut cultivation was a family tradition and how they defined themselves regarding chestnuts. Characteristics on chestnut stands such as tree number and age as well as systems multifunctionality were compiled. In section (2), there was an open question, asking for the three main motivations for chestnut cultivation. Questions on aims and challenges had a Likert-scale format as described for article II. Section (3) focused on ecosystem services provision. To evaluate the perceived association between certain ecosystem services and annual versus perennial crops, I provided respondents a Likert-scale. The number 1 indicated that the ecosystem service was associated with annual agriculture, 2 meant rather associated with annual agriculture, 3 meant not allocated or allocated with both, 4 represented an assignment rather to perennial staple food crops, and 5 meant that the ecosystem services were assigned to perennial staple food crops. Concerning measures for upscaling chestnut production and consumption in Germany, I gave predefined measures and asked respondents to indicate on a Likert-scale their perception on the easiness of implementation and how much impact on upscaling that measure would have.

Survey participants of article III had to fulfill the criteria of cultivating at least five chestnut trees for fruit production in Germany. The aim was to find and cover all German chestnut growers that meet these criteria. Therefore, existing contacts were harnessed, the internet was investigated and snowball sampling was applied. A total of 79 potential respondents were identified, of which I could finally interview 67. After obtaining informed consent, interviews were carried out by phone, and these were recorded and transcribed. Interviews were carried out from March to July 2022.

3.3. Data Analysis

Due to the exploratory character of my studies and the aim to show the results in a clear and easily understandable way, I used frequency analysis for driver categories in article I and for all nominal and ordinal data in article II and III. To do so, I calculated how many percent of respondents chose which answer category. For ordinal questions, I additionally calculated response mean values, to be able to rank answer categories according to mean values to show the relative agreement of respondents. In the case of article III, I sorted the three major motivations of chestnut growers to cultivate chestnuts (open-ended question) according to similar meanings and inductively grouped them according to similar characteristics, ending with six nominal categories.

In the articles II and III, I performed nonparametric statistical data analysis with the program SPSS. In the case of article II, I was interested in statistical differences between rural and neo-rural land managers, whereas in article III, I compared junior chestnut growers (up to 40 years) with senior growers (above 40 years), deriving age categories from other papers (Gullino et al. 2020; Zafeiriou et al. 2022). To compare ordinal data among the described groups, I conducted a Mann-Whitney U test. For article II, I applied this analysis to wildfire impact, wildfire measures, motivations, barriers, initiatives outcomes, success factors, and policy support. For article III, the Mann-Whitney U test was used for motivations, aims, challenges as well as perceptions on outcomes and measures for upscaling. I distinguished statistically significant differences in responses with a significance level of $p<0.05$.

In article III, I additionally conducted pairwise comparisons between responses for junior and senior growers on nominal data, covering questions on the personal background of chestnut growers as well as on chestnut stands. I used SPSS for the Chi-square test, also with a significance level of $p<0.05$.

3.4. Limitations

The integral complexity as well as the interrelated drivers of landscape change make research challenging. Case studies are a suitable approach to inductively derive common and diverging patterns of e.g. landscape change (Angelstam et al. 2013). However, it must be borne in mind that generalization, without questioning the results, is not possible due to its complexity. Limited scientific literature availability in the first article for some of the landscapes could have led to a certain vagueness of some landscape histories and their driving forces, especially for the southern fringe of the Mediterranean Basin. Therefore, I conducted interviews with experts for these three landscapes. The case study landscapes of the northern Mediterranean fringe completely relied on scientific literature and potential errors could have been reproduced.

Interviews always represent the perceptions of respondents, which are based on the social-ecological context they live in (Bernard 2018). The results can be also be influenced by norms, for example, respondents may think that certain answers are favored by the interviewer. The interpretation of the results of article II was only possible as I had a native Spanish speaker who was also a local expert amongst my co-authors.

4. Study Areas and Research Objects

4.1. Mediterranean Basin – Ecozone Scale

Figure 5: Tree crop landscapes of cork oak, sweet chestnut, and olives. The pictures are extracted from article I.

The first article covered the Mediterranean Basin, an ecozone scale. Three iconic tree crops, that shape the Mediterranean Basin, already exist for a long time, and represent important resources of human subsistence, were selected, namely cork oak (*Quercus suber*), chestnut (*Castanea sativa*), and olive (*Olea europea*) (Figure 5). Such tree crop landscapes are closely linked to the history, livelihoods, and culture of people living here and exhibit different land-use intensities. For each of the selected tree crops, I analyzed three study landscapes. I selected the landscapes with the best availability of literature on landscape history and driving forces of land-use change as my case studies.

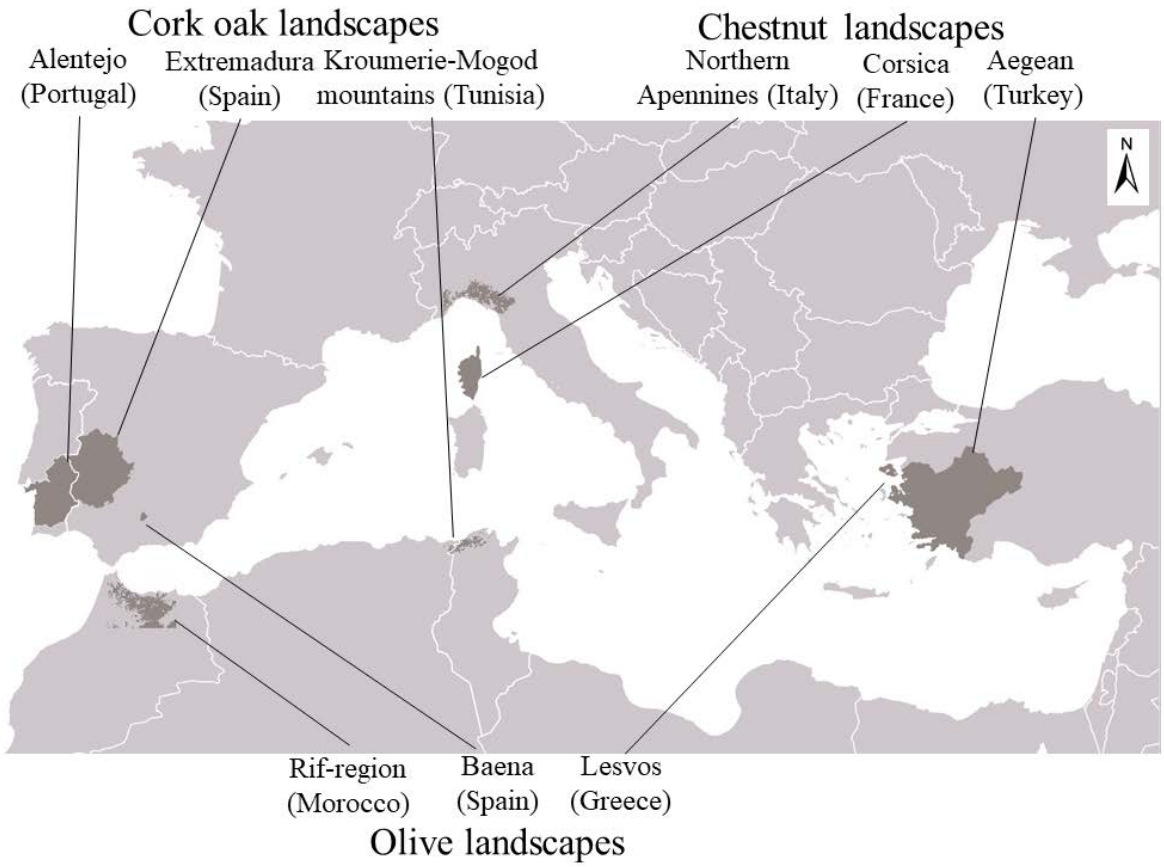

Figure 6: Map of chosen tree-crop landscapes. Taken from article I.

The nine case study landscapes are depicted in Figure 6, and in short described here. The cork oak landscape in Alentejo, Portugal, is called *montado*, characterized by scattered trees, dominated by

oaks, and extensively grazed with livestock (Muñoz-Rojas et al. 2019). In the Kroumerie-Mogod Mountains in Tunisia, cork oak represents the most abundant native tree species and is a key income for the local population (Campos et al. 2008). The scattered oak landscapes in Spain are called *dehesas*, grazed by livestock, and have probably existed since prehistoric times (Stockwell 1947). The steep mountains of north-eastern Corsica (France) and the history of the Corsicans has been shaped by chestnut trees, which led to the region´s name La Castagniccia. In the Apennines in Italy, chestnuts have dominated a mosaic of agroforestry systems, served as a staple food crop, and have shaped the culture of people living there (Agnoletti 2007). The Aegean region in Western Turkey is a mountainous region that has been shaped by chestnut cultivation, which had also an impact on people´s traditions (Avanzato 2009). Lesvos is a Greek island, which mountainous landscape and cultural identity have been shaped by olive plantations (Kizos et al. 2010). Baena, a municipality in Andalusia, Spain, is the region with the world´s most concentrated and specialized olive oil production having about 70% of the land surface covered by olives (Infante-Amate and Molina 2013). The Rif-region of Morocco is the center of olive production. In this region, olives trees are a sign of wealth and are closely connected to people´s daily lives (Kholy 2012).

4.2. Sierra de Gata and Las Hurdes, Spain – Regional Scale

Figure 7: Impressions of the case study area. Agroforestry landscapes for wildfire mitigation. Livestock herding, scattered tree crops, and thinning of forests are measures of wildfire mitigation. First picture extracted from article II, all pictures taken by field assistants.

The case study area of the second article is on a regional scale, covering diverse landscapes (Figure 7). I conducted my research in the rural, adjacent counties of Sierra de Gata and Las Hurdes in Spain, which belong to the northern Cáceres Province of the Extremadura Autonomous Region in Western Spain. Sierra de Gata comprises 19 municipalities and covers 1257.94 km². Las Hurdes covers 499.37 km² and consists of six municipalities (IEEX 2021). The area has a typical Mediterranean climate, shaped by wet and mild winters and dry, hot summers. The remote and mountainous regions are mainly covered by shrubland, cropland, pastures, and forests (Figure 8). Traditional agroforestry landscapes have been substantially transformed first in Las Hurdes (since the 1930s) and later in Sierra de Gata (since the 1960s). Forest fire occurrence increased at the time of a massive pine plantation establishment fostered by the Franco regime (1940-1975) (Iriarte-Goñi and Ayuda 2018). Since the 1950s, enhanced outmigration fostered by industrialization and socio-economic crises has left an overaged society (Madruga et al. 2021). Outmigration also caused the abandonment of livestock grazing and land management, which resulted in shrub and forest encroachment and flammable biomass accumulation (Iriarte-Goñi and Ayuda 2018). Mediterranean climate with mild and wet winters and hot and dry summers is wildfire-prone. Alone in Sierra de Gata and Las Hurdes, 2.298 wildfires burned an area of 37.500 ha between 2000 and 2015 (Bertomeu et al. 2019). One of those wildfires is shown in Figure 8.

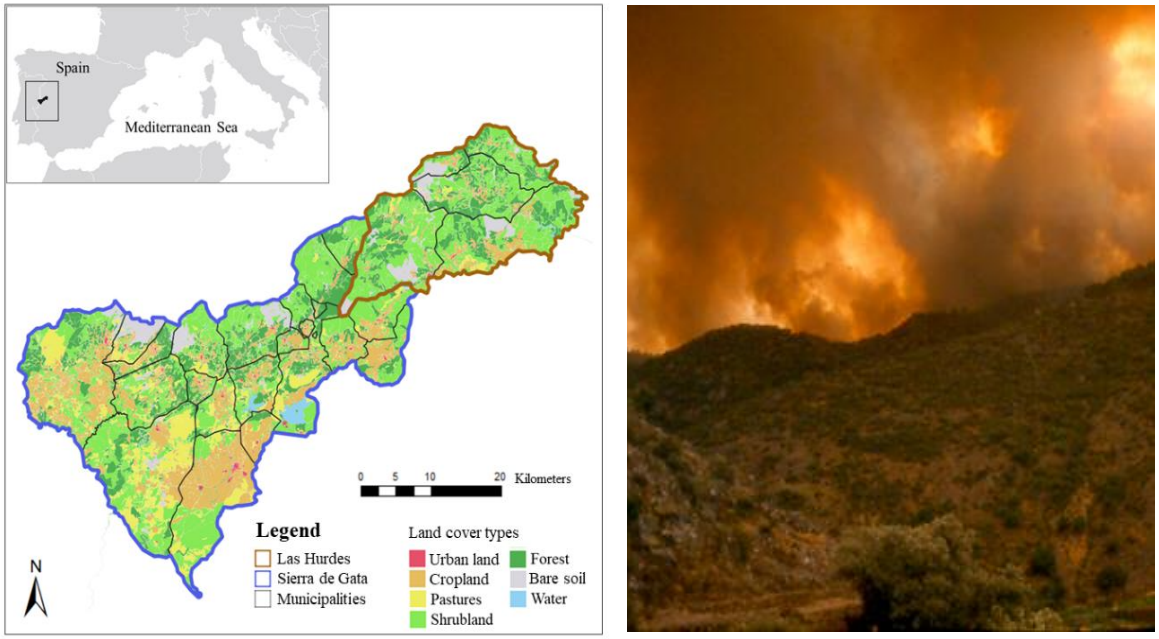

Figure 8: Left: Map of Sierra de Gata and Las Hurdes, extracted from article II. Right: Wildfire in the study region, picture taken by Fernando Pulido.

Although fire number and size of burned areas decreased between 1983 and 2021, the fraction of large (>500 ha) or very large fires (>5000 ha) increased (Ministerio de Transición Ecológica 2022). A single mega-fire burned nearly 8000 ha of Sierra de Gata (Bertomeu et al. 2022). In the region, the current focus of authorities is rather put on wildfire suppression strategies (like increase in fire-fighting equipment) than on treatments that mitigate the causes of mega-fires which would be biomass removal treatments like livestock grazing. The described study area was chosen as it is home of the Integrated Landscape Initiative *Mosaico*. In the following text, the study sites will be referred to as Gata-Hurdes. The main objective of the initiative is a collaborative engagement in wildfire mitigation through the use of productive fuel breaks, which are areas maintained by agroforestry (Varela et al. 2020).

4.3. Germany – National Scale

Figure 9: Sweet chestnut: Fruits, chestnut tree and planted chestnut orchard.

Chestnuts are trees that can be used in a multifunctional way. In the late Middle Ages (ca. 1250-1500 AD) chestnuts were cultivated for fruit production and increasingly seen as valuable trading goods also for trade with other countries (Bouffier and Maurer 2009). In the second half of the 18th century, chestnut coppices were common in regions of grape production as the wood was used for lattice posts. Chestnuts were an important food source in Germany during and after the two World Wars. However, the high demand for tannin, firewood, and timber led to the over-exploitation of chestnut trees (Bouffier 2018). Through the change in eating habits after World War II, chestnuts lost their importance as a food source (Bender 2002). Chestnut blight (*Cryphonectria parasitica)*, a fungal disease spread in Germany since 1992 (Wall and Aghayeva 2014) became a major driver of chestnut decline, especially in other European countries where chestnuts are more common (Pezzi et al. 2017). Hence, chestnut cultivation and breeding in Europe will be mostly based on hybrids of *C. sativa* with disease tolerant Asian chestnut species (*C. crenata* and *C. mollissima*) (Ecker et al. 2018).

There is a revival of chestnut cultivation and a comeback of appreciation in the last decades in Germany and elsewhere (Bouffier 2019; Davison et al. 2021). A newly planted chestnut grove is shown in Figure 9. Chestnuts are valued for their multifunctionality not only regarding provisioning ecosystem services but also for regulating, supporting, and cultural services they offer (Conedera and Krebs 2008). Most chestnut trees in Germany are located in mature forests, accounting for about 7500 ha only (Bouffier and Maurer 2009). Areas, that are known for their chestnut cultivation, are the regions Haardt and Dannenfels in Rhineland-Palatinate, the Taunus which is an upland in Hesse, and the West of Southern Germany.

5. Results and Discussion

This chapter extracts central themes of my articles that contribute to the overarching aims of the thesis. I distinguished and discussed the three articles according to a past, present, and future perspective. The result section will include the results of all three articles following the structure described in Figure 10.

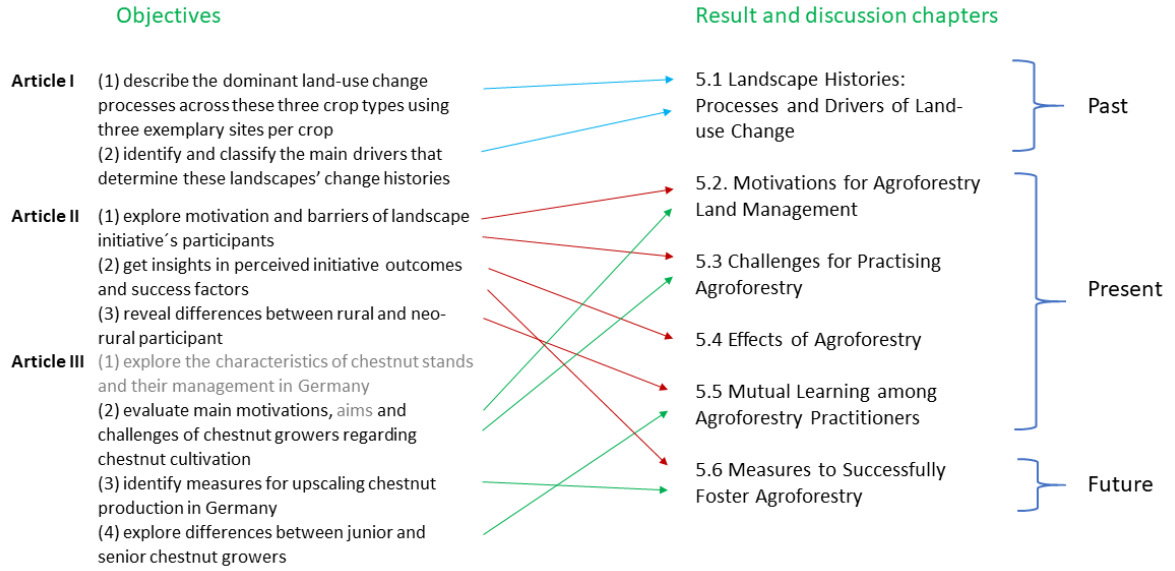

Figure 10: Structure of the result and discussion chapter on basis of the research objectives, covering past, present, and future. The research questions in grey are not covered in this thesis.

5.1. Landscape Histories: Processes and Drivers of Land-use Change

In article I, I developed nine landscape histories that were compiled into landscape narratives. These contain the main processes of landscape change as well as its driving forces. The six landscape processes I derived from the literature were expansion (growing extent), continuity (no significant change), intensification (increasing management effort and yield), abandonment (decreasing management effort and yield), polarisation (land abandonment and intensification), and renaissance (a renewed management after a phase of abandonment). The predominant landscape processes of the nine tree landscapes since 1800 are depicted in Figure 11. I found that each of the nine landscapes had a unique history, although common patterns of processes and drivers could also be detected. It should be emphasized that the tree crop landscapes, at the beginning of the 19th century, were either in a phase of expansion or continuity. In the last decades they either underwent a phase of intensification, abandonment, polarization, or renaissance. These diverging trends were also found in a study on land-change hotspots (Kuemmerle et al. 2016). An overall increased dynamic of landscape change was notable. This is important to recognize for future scenarios in land-change models, as dynamics affect scenario outputs (Liu and Andersson 2004).

Revitalization of tree crop landscapes is a recent trend that took place in the chestnut landscape in France and the cork oak landscape in Spain. Simultaneously, a new approach to the collaborative management of landscapes arose, the so-called Integrated Landscape Initiatives (García-Martín et al. 2016).

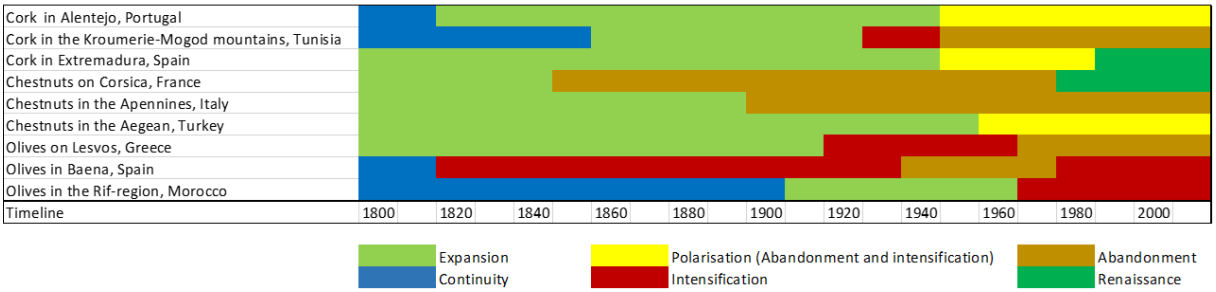

Figure 11: Landscape processes of the nine tree crop landscapes. Extracted from article I.

I categorized the drivers of change into five groups, namely socio-cultural, political, technical, economic, and natural drivers. The landscape processes with associated drivers are depicted in Table 2. I found that landscape changes have multiple, often also interrelated drivers. Many socio-cultural drivers appeared, which are highly complex and often neglected in debates on driving forces of landscape change (Bürgi et al. 2004), such as cultural identification, or changing lifestyle. I showed that cultural identity was a driver of expansion, such as in the cases of Portugal and France. The multiple demands and a livelihood that depends on the landscape were also driving expansion in historic times. However, a changing lifestyle led to the opposite: If young people are out-migrating from rural landscapes, labor shortages lead to abandonment as I have shown in the French case as well as for Italy and Greece. In all three cases, this was combined with a missing profitability or economic crisis. Profitability was crucial on the landscape scale, as maintaining a whole landscape requires substantial effort that cannot be achieved as a hobby, but has to provide a livelihood for the people living on the land (Howkins 2003). I also found that abandonment was either directly or indirectly linked to missing profitability.

Table 2: Types of driving forces for landscape change. Extracted from article I.

Type of drivers				
Socio-cultural	Political	Technical	Economic	Natural
Over-exploitation	Land development plans	Technological progress	Low demand for crop	Pests or diseases
Livelihoods	War	Mechanisation	Demand for crop	Drought
Multiple demands	Privatisation of land	Agrochemicals	Missing profitability	Fire
Specialised demand	Market liberalisation		Profitability	
Population growth	Land-use restrictions		Marketing strategy	
Outmigration	Agricultural subsidies		Economic crisis	
Changing lifestyle	Conservation programmes		Economic growth	
Cultural identification				
Community decisions				
Awareness				

The underrepresentation of drivers of continuity in studies was highlighted by Plieninger et al. (2016) and identified as an important counterbalance for drivers of change (Bürgi et al. 2004). I also discovered that the drivers of continuity were rarely reported. However, in the olive landscapes of Spain and Morocco, the drivers of continuity were, that the landscapes provided the basis of livelihood of people as well as multiple provisioning services, such as fruits and timber. In contrast, specified demand was repeatedly leading to the intensification of land-use. The drivers of renaissance are

particularly interesting: In the two respective cases, I found a combination of conservation programs, marketing strategies, and profitability as drivers for the cork oak landscape in Spain and a combination of awareness, community decisions, and technological progress for the chestnut landscape in France. In the review of driving forces in European landscapes, cultural drivers were found as key for rural development initiatives (Plieninger et al. 2016), which could for example be an awareness for the need of sustainable land management. Understanding the drivers of these landscape processes can help to guide future land-use and decision-making processes.

I found that land-use restrictions can be drivers of expansion, abandonment, as well as intensification. This highlights the large potential of political decisions but also points towards the responsibilities of decision-makers, who might not only influence restrictions but also subsidies. My findings are supported by a European review on driving forces highlighting political drivers as one of the major drivers of intensification and abandonment (Plieninger et al. 2016). According to the Millennium Ecosystem Assessment, local decision-makers can have an influence on land-use changes as well as on influencing technology and external input choice. The decision-makers on larger spatial scales can impact macroeconomic policy, prices, markets, and trade barriers for goods as well as property rights (MEA 2003).

5.2. Motivations for Agroforestry Land Management

In article II, I discovered that land managers of the Integrated Landscape Initiative were highly motivated by multiple motives. These are depicted in Figure 12. Interestingly, the strongest motivation was combatting depopulation. This is understandable considering that about a third of the population was lost between 1960 and 1975 in the region due to emigration (Rosado 2018). This motivation could imply that the initiative offers perspectives for people to make a living from the land. Preserving landscape beauty, as the second important motivation, shows, that aesthetics play an important role in people´s well-being and that the connection to the traditional landscape could have created a sense of identity (Roux et al. 2022). A review of Integrated Landscape Initiatives in Europe showed similar results (García-Martín et al. 2016).

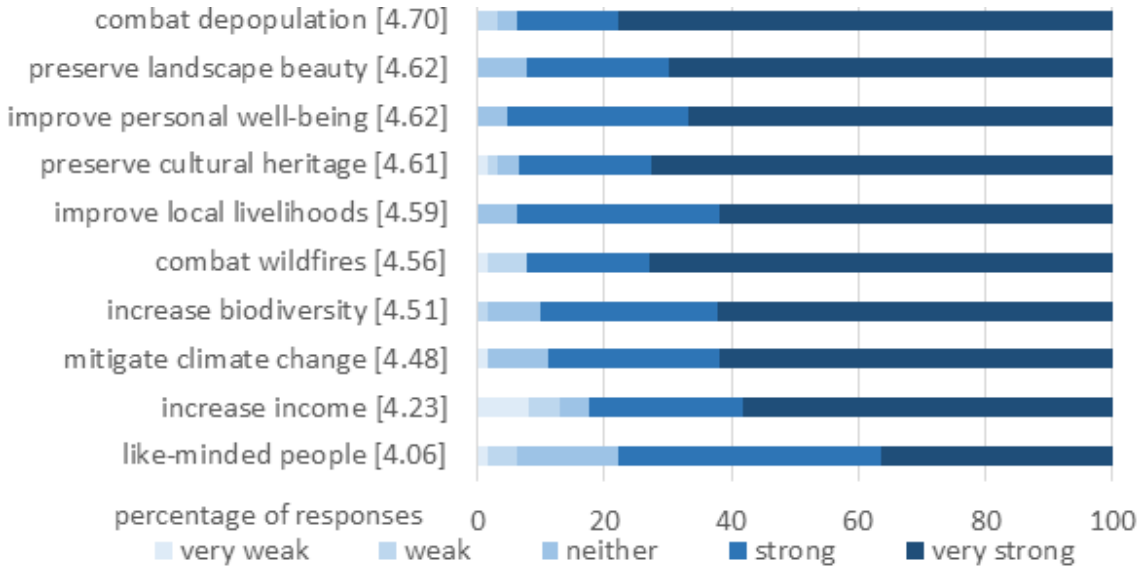

Figure 12: Motivations of Mosaico farmers to collaboratively manage land. The color intensity expresses answer categories. Numbers in brackets are the means of the response values. Extracted from article II.

The four highest-ranked motivations were socio-cultural motives. Increased income was one of the weakest motivations for collaborative land management, however, still mentioned by over 80% of

respondents as a strong motivation. Combatting depopulation as the strongest motivation can be linked to profitability. Its absence leads to the abandonment of landscapes, as found in article I. The low-ranked motivation of increased income might rather reflect the results of Oviedo et al. (2017), who found that farmers are often similarly or more motivated by the advantages of living in nature or by their lifestyle than by profits. Combatting wildfires was a strong or very strong motivation for over 90% of respondents, which was also discovered by land-owners being part of a Californian land-owner cooperation (Ferranto et al. 2013). However, the strong motivation by nearly 90% of the land-managers to mitigate climate change is surprising, as former studies found very low awareness regarding climate change among farmers globally (Madhuri and Sharma 2020; Saliman and Petersen-Rockney 2022).

In article III, I asked in an open question for the respondent´s three main motivations to cultivate chestnuts. The motivation most often mentioned was climate change mitigation and adaptation (mentioned by 36% of respondents). Thereby, a major global threat is displayed, as trees not only are a measure for adapting to changing climates but also have an important mitigation potential (IPCC 2019). The second most frequently mentioned motivation was food production (23%), followed by aesthetics (22%). An alternative for annual agriculture was mentioned by 20%, and this relates to chestnuts as perennial staple food crop being potentially more sustainable than annual food crops. The same number mentioned biodiversity as one of three motivations. After grouping motivations into six categories (cf. Table 3), I found that motivations related to sustainable food production were mentioned most often (73% of respondents named such motivation at least once).

Table 3: Motivation of respondents to grow chestnuts. All motivations listed here were at least named twice. They were allocated to motivation categories. The percentages show the share of respondents mentioning these motivations. Taken from article III.

Sustainable food production	Personal well-being	Multifunctional uses	Landscape restoration	Added value	Socio-cultural motivation
Climate change mitigation and adaptation [36%]	Aesthetics [22%]	Food production [23%]	Biodiversity [20%]	Innovation [19%]	Connection [8%]
Alternative for annual agriculture [20%]	Fun/pleasure [17%]	Honey plant [9%]	Multifunctionality for the environment [6%]	Marketing [6%]	Knowledge transfer [6%]
Subsistence [8%]	Gusto/taste [8%]	Multifunctional uses [8%]	Shade [3%]	Added value [3%]	Food sovereignty [5%]
Regionality [6%]		Wood [5%]		Low maintenance effort [3%]	Awareness for transformation [3%]
Diversification of production [6%]					
Resilience [6%]					
Longevity [6%]					
Orchard meadow conservation [5%]					
Vital tree [3%]					

It was followed by personal well-being (41%) and multifunctional uses (36%). Although nobody directly mentioned profitability or earning money as motivation, the motivations of the category added value are related to economic motivations. Furthermore, I found in a Likert scale question that over 60% aimed to earn money with the chestnuts. In contrast, income and soil erosion control were the highest motivation to implement agroforestry in the southern Philippines (Magcale-Macandog et al. 2006). This reveals that there are many reasons for agroforestry adoption that are dependent on the socio-ecological context.

As motivations were asked in different ways for article II and III, the results are not one-to-one comparable. The open question provides a clearer picture of motivations as answers are not predefined (and only three motivations were allowed), but the results are more difficult to interpret because of answer diversity. I found common patterns of motivation in article II and III. Mitigating climate change was a high motivation for farmers in Spain and played a major role in motivating chestnut growers in Germany. Another motivation of high importance for both groups was preserving landscape beauty/aesthetics, which is also one of the most often mentioned cultural ecosystem services in a review on cultural Ecosystem services and well-being (Kosanic and Petzold 2020). In article II and III, enhancing biodiversity is a common motive for managing agroforestry systems, and this is also discovered by García de Jalón et al. (2018) for European agroforestry stakeholders. Fighting depopulation seems to be a motivation only in the case of article II. One reason could be the history of abandonment in the rural areas of Gata-Hurdes, but also that the collaborative approach of the initiative seems to offer perspectives for livelihoods. On the contrary, an alternative for annual agriculture as well as a connection to other people and nature were very important motivations for chestnut farmers but were not mentioned as missing answer categories by respondents in Spain.

5.3. Challenges for Practicing Agroforestry

In article II, I found that some challenges for collaborative agroforestry management affected many, whereas others only affected only a few farmers (cf. Figure 13). The strongest challenge to farmers by far was the lack of adapted legislation with 82% of respondents regarding it as a high or very high barrier. Additionally, 65% were faced with high or very high challenges caused by a lack of political support.

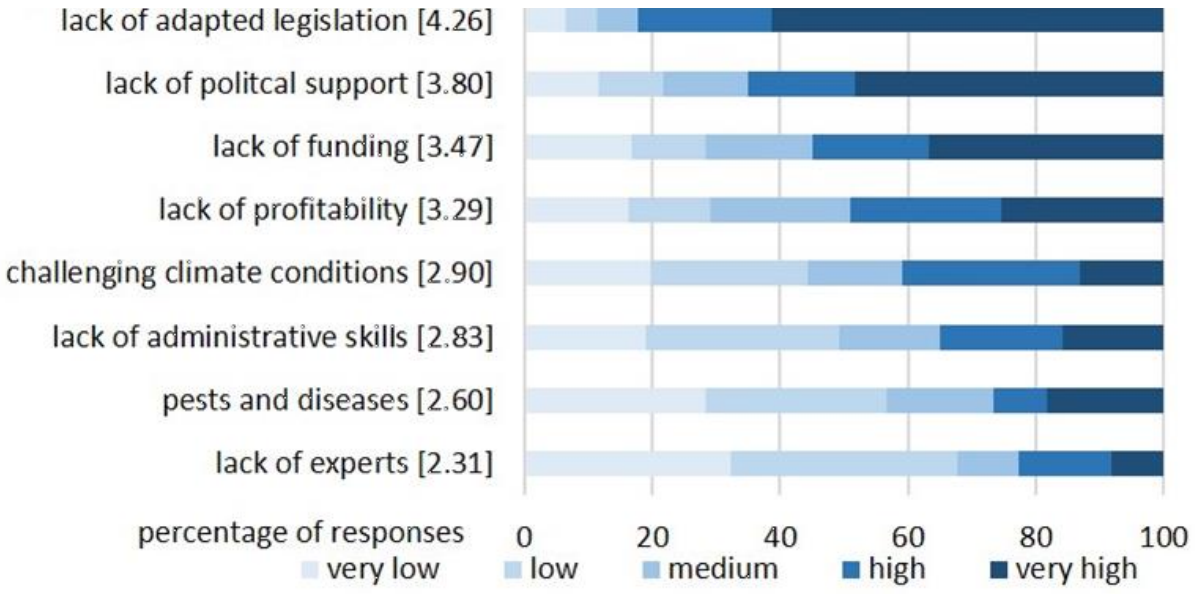

Figure 13: Barriers to collaborative agroforestry management. Numbers in brackets are the means of the response values. Taken from article II.

Still, 55% suffered from a lack of funding. In other European Integrated Landscape Initiatives, lack of funding was by far the major challenge (García-Martín et al. 2016). The unadapted legislation, pointed out by the respondents, may be regional and national regulations that often prohibit grazing in forests and restrict transformation to agricultural land. Among other professional groups, farmers particularly often faced narrow and inflexible policies that were not adapted to the local context (García-Martín et al. 2016). Climatic conditions were already problematic for 41% of respondents.

In article III, the challenges for chestnut cultivation differed not much in their extent among growers (cf. Figure 14), showing mean values around three out of five. However, missing long-term thinking of institutions was the highest-rated challenge, as 66% mainly or fully agreed. The second highest barrier was a missing traditional connection to chestnut culture and cultivation (58% of respondents mainly or fully agreed). Too low yearly subsidies have closely followed with 57% of responses in these categories.

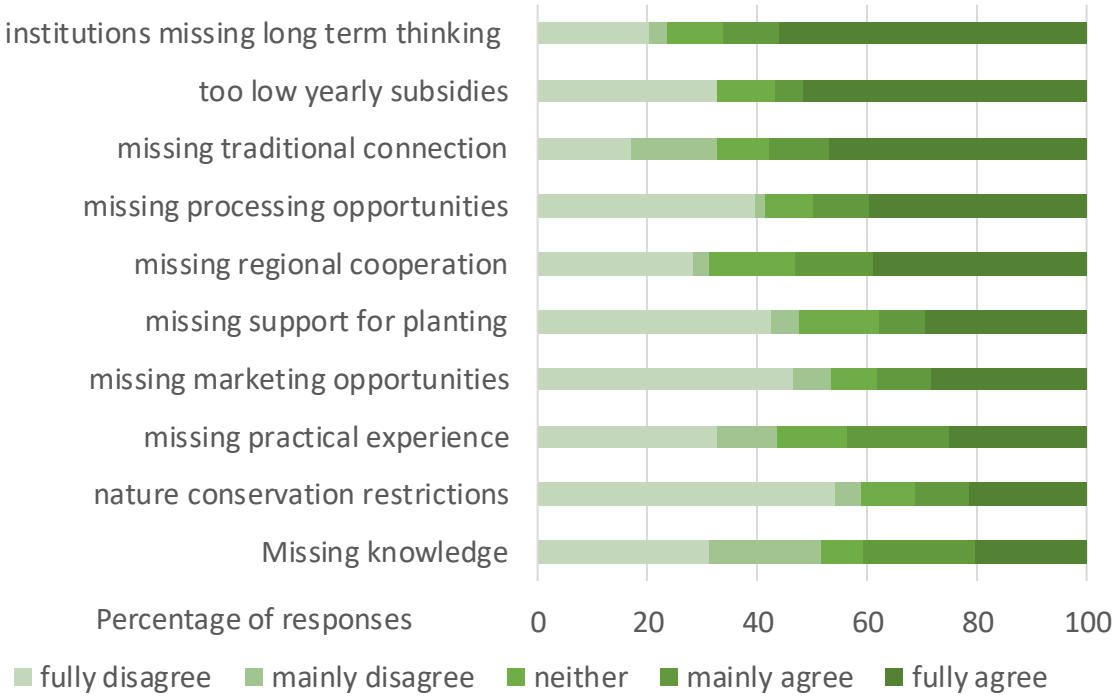

Figure 14: Barriers for chestnut cultivation in Germany. Taken from article III.

Both a lack of adapted legislation (in article II) and institutions missing long-term thinking (in article III), refer to policies that are not adapted to agroforestry land management. In both cases, it is the highest-ranked barrier. It was also an important driver in the tree crop landscape histories as discussed above. Although agroforestry systems are seen as important contributors to solutions for different global challenges including climate change and soil erosion (IPCC 2019; Willett et al. 2019), policies lack adaptation to foster the transition towards more multifunctional and complex land-use systems (García de Jalón et al. 2018). Too low subsidies and funding are also among the highest-ranked barriers in both cases (article II and III). Subsidies can have a high effect on the profitability of a certain crop. As I showed, subsidies were one major driver of landscape change (article I). Missing knowledge or a lack of experts were the lowest barriers in both cases (article II and III). The histories of tree crop landscapes rather showed that it was a lack of work force due to outmigration that led to the abandonment of landscapes. This implies that there is a need to increase the attractiveness of multifunctional land management. The missing traditional connection to chestnut culture and cultivation was an important barrier for chestnut growers in Germany (article III). In the landscape

histories (article I), this connection was referred to as identity and was an important driver of tree crop expansion. The tree crop histories (article I) showed that challenging climatic conditions like drought can lead to intensification and abandonment (cf. Portugal and Tunisia) and were also a barrier to *Mosaico* farmers (article II). In Germany, the last five years showed a strong increase in drought intensity (Boeing 2023), probably a harbinger of climate change. This implies that barriers such as challenging climate conditions and wildfires could also play an increasing role in current temperate climate zones as with climate change high temperature and increasing weather extremes are expected.

5.4. Effects of Agroforestry

I found diverse positive outcomes of agroforestry systems in both temperate and Mediterranean climates. For the Mediterranean climate, I found manifold personal and regional effects of the collaborative management of agroforestry landscapes, which are the results of social collaboration as well as of agroforestry systems. As I showed in article II, the highest perceived regional outcome of collaborative agroforestry was combating wildfires (86% agreed or strongly agreed). This was followed by increased local ecological knowledge, enhanced biodiversity, and more sustainable land management (over 80% of agreement, respectively). Over 50% also attributed counteract abandonment, improve the regional economy, and increase the well-being of locals as outcomes of collaborative agroforestry. The highest-rated personal outcome was more enthusiasm for traditional land management (72% agreement). The personal outcome with the highest percentage of strong agreement was that both, collaboration and support from the initiative, helped to overcome administrative barriers.

In article III, I asked respondents if they would allocate certain ecosystem services more toward perennial food crops or annuals. The mean answer for all ecosystem services outcomes tended more towards the provision through perennial food crops. The ecosystem service, that was most clearly matched to perennial food crops was biodiversity with 98% of respondents allocating it to perennials and 2% allocating it neither to annuals nor to perennials. Biodiversity was also a strong motivation for chestnut cultivation as shown above. My results are supported by a study on chestnuts in Greece where 94% of respondents attributed an increase in biodiversity to agroforestry systems (Zafeiriou et al. 2022). The increase in structural complexity as well as habitat and landscape heterogeneity due to trees and shrubs in agroforestry systems has a high potential for increasing biodiversity (Torralba et al. 2016). As shown above, an increase in biodiversity was not only a high motivational factor but it was also perceived as an outcome of (collaborative) agroforestry systems in the *Mosaico* case in Spain, as well as for chestnut growers in Germany. As depicted in the ecosystem services and well-being framework (Figure 2), biodiversity is the basis for other ecosystem services. This is supported by our findings in which agroforestry systems foster biodiversity as well as other ecosystem services. These ecosystem services directly affect people´s well-being, as it can be seen in the framework as well as in the results of articles II and III as agroforestry outcomes.

If there are no sufficient mitigation strategies such as collaborative agroforestry, wildfires can create high damage to the landscape and people and even be a driver of abandonment of landscapes as shown in the case of Tunisia in article I. If wildfires increasingly occur in temperate climates, agroforestry systems may also be valued in a similar way to my results of article II. In Germany, wildfires already destroyed an increasing amount of land in the last years with a peak in 2022 of 4,293 ha (STATISTA 2023). With climate change, droughts are expected to increase, and hence wildfires, too.

5.5. Mutual Learning among Agroforestry Practitioners

Nearly half of the respondents in article II were neo-rurals. They are characterized as people that move from the city to the countryside as a response to industrial agriculture and unsustainable city life (Escribano and Mormont 2007). Neo-ruralism is an increasingly common trend in Europe and therefore getting enhanced attention (Bender and Kanitscheider 2012; Dal Bello et al. 2021). Comparing neo-rural to rural respondents, I found statistically significant differences in their motivations: Neo-rurals were stronger motivated by the opportunity to increase biodiversity, grow their own food, and improve personal well-being. These are also general motivations of neo-rurals for leaving former city life (Orria and Luise 2007; Dal Bello et al. 2022). However, I found that climate change was a stronger motivation to collaboratively manage agroforestry systems for rurals. This may be explained as they have experienced the increase of climate extremes like droughts in the last decades.

In article III, I found statistically significant differences across junior and senior chestnut growers for three motivation categories. Juniors more often mentioned motivations that I pooled in the category of sustainable food production, whereas seniors rather tended to mention personal well-being and multifunctional uses as motivations. I also found that seniors were more often isolated whilst juniors were better connected to other chestnut growers.

In both surveys (article II and III), most of the differences among groups (neo-rural/rural and junior/senior) occurred in motivations. In the light of increasing abandonment of rural agricultural landscapes, the movement of neo-ruralism could provide new opportunities for the revitalization of rural economies and the maintenance of cultural landscapes (Pérez and Gurría 2010; Del Romero Renau 2018). The increased motivation towards pro-environmental performance and global thinking could prosperously complement practical experiences and local ecological knowledge of rurals. Similarly, the higher motivation for sustainable food production of junior chestnut growers and their better connection amongst each other could give hope for stronger implementation of agroforestry practices in the future. While junior growers can take advantage of the long-term experience of senior growers, seniors can learn being better connected to other growers in Germany but also world-wide through social-media.

5.6. Measures to Successfully Foster Agroforestry

Having asked respondents of article II on success factors for collaborative agroforestry, fighting a common and immediate risk like fire was regarded as one of the most important parameters (97% find it important or very important). As climate change is an ongoing process and the effects of human action is challenging to assess, our results could help to explain the difficulty in implementing measures to mitigate climate change. Cooperation between different stakeholders and sectors was seen as an equally important success factor, followed by knowledge sharing and active participation with similar results. This supports the importance of mutual learning among agroforestry land managers described in the chapter above.

In article III, I provided different measures that could enhance the production and consumption of chestnut cultivation and by that the implementation of agroforestry. The respondents had to specify their perception of how easy these measures are to implement and how high they assess the impact on the production and consumption of chestnuts. The results are shown in Figure 15. Blue lines indicate the mean value of all measures. The highest impact for upscaling chestnut cultivation is expected due to better funding (mean 4.50) followed by breeding disease-tolerant trees (mean 4.37). The measures easiest to implement are creating a cultivation guideline (mean 4.27) and conducting seminars (mean

4.19). The measures in the right upper quarter are most critical as they are expected to be easy to implement and have a high impact, namely creating a cultivation guideline (mean implementation 4.27, mean impact 4.27), establishing lighthouse projects, networking, and creating variety gardens. As chestnut fruit cultivation is rare in Germany, all the measures, that are perceived as easy to implement and having a high impact (upper right quarter of Figure 15), are about a cultivation guideline, connecting people, and improving availability of model farms and plant material. All these measures are also listed as key needs for professionalizing chestnut cultivation in the US (Davison et al. 2021). The highest impact was attributed to better funding which is also a key need mentioned in the study on chestnut cultivation in the US (ibid).

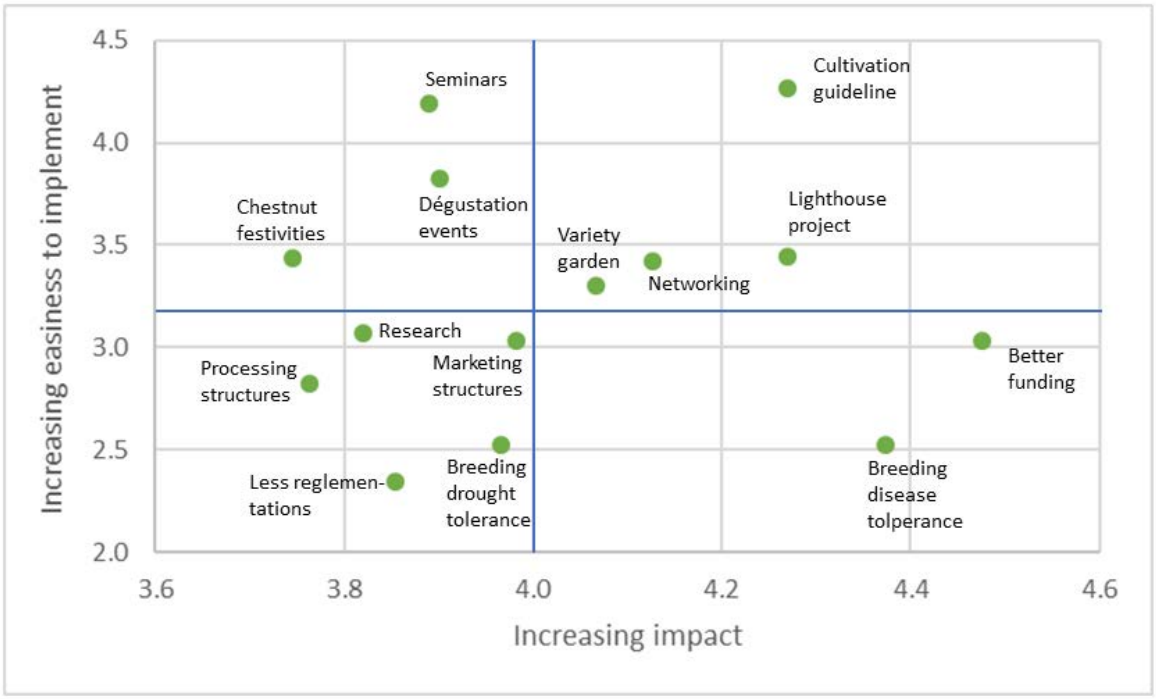

Figure 15: Measures for upscaling chestnut production and consumption in Germany. Respondents rated the given measures according to their perception of easiness to implement (from 1 to 5) 1=very difficult, 5=very easy) and impact on upscaling (1=very low impact, 5=very high impact) chestnut production and consumption in Germany. Measures are depicted as mean values with green spots. Blue lines show mean values across all measures to indicate critical measures in the upper right quarter. The figure is extracted from article III.

The results of article II and III are not directly transferable. In the former article, success factors for collaborative agroforestry were asked while in the latter article, the question focused on measures for upscaling chestnut production, having the focus on a single crop. However, both articles addressed how to successfully foster agroforestry in the future. My results in article III show the need for very basic requirements, such as knowledge and variety gardens for chestnuts. However, also socio-cultural factors such as networking and collaboration with different stakeholders are crucial (as also discussed in the chapter on mutual learning).

6. Conclusion

6.1. Major Findings

The main objective of this thesis was to get insights into land-use change from traditional multifunctional to simple annual systems and to explore ways to maintain and revive multifunctional agroforestry systems. Therefore, I first aimed to understand the histories of land-use changes across different landscapes.

In the first article, I compiled nine unique histories of olive, chestnut, and cork landscapes in eight different countries of the Mediterranean basin. I found common patterns of landscape processes and driving forces of change across different landscapes. There was a general acceleration of landscape change that took place in the last century compared to the century before. While most of the studied tree crop systems were in a process of expansion in the time from 1800-1900, the following century was shaped by phases of intensification and abandonment, especially in the second half of the 20th century. These processes were driven by complex and interrelated drivers that I categorized as socio-cultural, political, technical, economic, and natural. I found a surprisingly high number, occurrence, and importance of socio-cultural drivers, such as multiple or specialized demands, changing lifestyle or cultural identity. However, profitability seems to be key for maintaining whole landscapes as it needs too much effort to do that as a side activity. Demand for multiple products from the landscapes (such as for fruits, timber, and livestock grazing) fostered tree crop expansion. On the contrary, a specialized demand (like only for olives) led to either abandonment on marginal sites or intensification on favorable sites. In recent decades, a new process occurred that I called renaissance: The revitalization of traditional tree crop landscapes due to drivers such as new marketing strategies, nature conservation programs, and awareness. With this article, I contributed to the social-ecological understanding of complex driving forces and processes of agroforestry landscape change that can guide future decision-making.

The second article focused on a case study of collaborative agroforestry in Gata-Hurdes in Spain to mitigate wildfires. I found collaborative agroforestry was perceived as a successful way for wildfire mitigation, including manifold other positive personal and regional benefits, such as enthusiasm for traditional land management, biodiversity, and counteracting abandonment. Respondents were highly motivated, mostly by counteracting the decreasing depopulation. Lack of adapted legislation was the strongest challenge, even higher than lack of funding, which was also a serious barrier. Interestingly, fighting a common and immediate risk was seen by nearly all respondents as a success factor for collaborative agroforestry. An especially high number of respondents were neo-rurals, people that return to the rural areas searching for a more sustainable lifestyle. These people could fruitfully complement rurals in their abilities and revive rural landscapes. With this article, I shed light not only on an innovative way of wildfire mitigation but also on an opportunity for the valorization of agroforestry landscapes, as wildfire mitigation is a further reason for the multifunctional use and management of such landscapes. I also highlight the role of neo-rurals in their underestimated contribution to sustainable landscape management.

In the third article, I aimed to assess the status quo of chestnut cultivation in Germany as a case study of an innovative perennial staple food crop integration in traditional and modern agroforestry systems. I found that chestnut growers were highly motivated by diverse motivations, mostly by motives I allocated to the category of sustainable food production. Climate change mitigation and adaptation was the most common motivation mentioned, indicating high awareness of climate change and the

chestnut tree as potentially being adapted to future climates in Germany. The biggest challenge was institutions missing long-term thinking, which is necessary if dealing with perennial crops. Too low yearly subsidies and missing connection to chestnut culture followed as barriers. This shows the importance of the profitability of land management but also the relevance of identity and connection to food and its production landscapes. Respondents allocated all given ecosystem services such as biodiversity and carbon sequestration towards perennial crops rather than annuals, except for food production which was nearly equally attributed to both. I found junior growers to be stronger motivated by sustainable food production and better connected to each other compared to senior growers. The most impactful measure for upscaling chestnut production and consumption in Germany was perceived as creating a better funding situation for agroforestry. However, if combined with easiness of implementation, a cultivation guideline, lighthouse projects, and networking seem to be the most critical measures.

This thesis sheds light on histories of multifunctional tree crop landscapes and current challenges, motivations, and outcomes of agroforestry management in temperate and Mediterranean climates. It covers challenges that are faced in many places of the world such as land-use polarisation and wildfires and offers insights into strategies for regional solutions, such as collaborative agroforestry and the integration of new tree crops in traditional landscapes.

6.2. Insights for Future Land Management and its Policies

The multifunctional tree crop landscapes that I studied harbored high biodiversity and multiple ecosystem services while forming a local identity. In the last century, they were abandoned or intensified due to different drivers, most importantly a changing lifestyle and missing profitability. Positive environmental outcomes of multifunctional agroforestry systems are well-known in the literature and confirmed by my respondents. They saw socio-cultural outcomes such as reviving the rural areas and enhancing landscape beauty as a result of their multifunctional land management and were highly motivated. However, they faced serious barriers that hampered agroforestry farming. Barriers have to be reduced as society is highly dependent on land-managers and their treatment of ecosystems and its effect on biodiversity. My respondents were very innovative land-managers that found ways to cope with challenges and maintain productive and multifunctional agroforestry systems. However, there are many land-managers worldwide that do not have the opportunity to produce food with positive outcomes on ecosystems as they are under high financial pressure.

The responsibility for sustainable land management has to be carried by the whole society, as we are all consumers of the food produced in these landscapes and hence are responsible for the effects. Eating diverse fruits as well as nuts and grass-fed outdoor meat as staple food could create diverse and multifunctional tree crop landscapes. Ideally, the role of farmers will change in future towards being creators of landscape beauty, providers of food, and savers of landscape sustainability. Media and education play an important role in transforming these norms.

In order to mainstream agroforestry practices that provide long-term sustainability, challenges like those my respondents faced have to be overcome. Decision-makers have large responsibilities in transforming the food system, for example by changing the allocation of subsidies. As the landscape histories showed, profitability is one key driver of landscape abandonment and intensification. Multifunctional agroforestry that enhances ecosystem services has to be supported as prices compete

with products that are based on the exploitation of nature and farmers trough industrialized and competitive annual agriculture. As diverse land-use systems are complex and need more effort to be managed, funding should especially support a high diversity of crops and perennial crops due to their high ecological value and benefit to human well-being in general. Tree crops as staple food crops are often neglected in their role in providing food and ecosystem services. Transparent and clear policies that are adapted to local contexts are needed. What we can learn from my respondents is to be innovative, collaborate and to personally contribute to a sustainable common future.

7. Personal Reflections

Since my childhood, I have felt deeply connected to nature and cultural landscapes. Playing and working on my father´s farm gave me deep insights into the challenges of working on the land, but also into the opportunity of having a sense of purpose. To me, the industrial agricultural model seems neither socially nor ecologically sustainable or acceptable. I studied geo-ecology to get a deeper understanding of the ecology of our planet and how to save it from the negative impact of humans. I found that the negative impact of food production is so immense that it is not enough to create nature conservation areas. We have to produce food sustainably if we want to sustain ecosystem health for future generations.

Following this aim, I got the great opportunity of a 50% position as a scientific employee working on the topic of agroforestry in the section of Social-ecological Interactions in Agricultural Systems at the University of Kassel, Germany. As I love holistic approaches and as agroforestry seemed to be a topic worth spending some years on, I moved to Witzenhausen to start this new chapter of my life. In the last five years, agroforestry grew from a marginal land-management practice and research topic to one major solution of a sustainable food system for the future. I had the opportunity to become one of the founding members of the German professional association for agroforestry (Deutscher Fachverband für Agroforstwirtschaft, in short DeFAF). Agroforestry not only became my research topic but also an integral component of my life. Fulfilling my teaching obligations, I had the opportunity to teach landscape stewardship in the bachelor course and agroforestry in the master course. I supervised many student reports, including 18 bachelor and master theses. I enjoyed being in contact with the students, the co-supervisors and getting insights on many different topics.

As my position was only a 50% part-time contract, I had time to start a side business, including a tree nursery, an agroforestry consulting business, and planting my own agroforestry system – all together with my partner Hendrik, whom I met in Witzenhausen. All of these activities fruitfully complemented each other. Scientific literature and research taught me a lot that I could implement on the land and vice versa. I also absorbed a lot of inspiration and motivation from working with the trees. It shows the fruits of your work in a more direct way than science. I can highly recommend such a practical side activity for physical and mental health. Two highlights were the field trip to Spain and Portugal in 2018 where we visited two of the tree crop landscapes from article I and Gata-Hurdes, where the organization *Mosaico* from article II is located, and the World Agroforestry Congress in Montpellier. I have enjoyed working with our research team a lot. Especially in times before the pandemic, there was a nice feeling of team spirit. The restrictions due to the pandemic hampered common activities, but in time, the awareness of the value of cooperation, physical meetings, and workshops rose.

In the course of these five years, I learned the importance of considering the context of any statement and scientific result. I found writing the discussion of the first two articles difficult, not knowing the language, the people, and the land-use systems of my study sites very well. I felt very dependent on local collaborators, but I was lucky that my partners felt very responsible for their tasks. I like the concept of transdisciplinarity a lot and also recognized the increased attention of public funding bodies. I hope that people with different backgrounds will be increasingly integrated into research projects and that it will be a central requirement by funding bodies. This should happen during an early-stage in order to include them in the process of developing research aims.

The last five years were a journey in which I learned a lot, including how much we do not know. I found the research topic of my life as well as a new home.

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I am deeply grateful for the past five years in which I wrote my thesis. I want to thank all people that contributed to my work, to my well-being, and to a common, more sustainable future, for example by creating beautiful landscapes of high cultural and ecological value, like the one in Figure 16.

Figure 16: New Forest Farm in Wisconsin US. Source: Mark Shepard.

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10. Appendix

Signed Declaration

I herewith give assurance that I completed this dissertation independently without prohibited assistance of third parties or aids other than those identified in this dissertation. All passages that are drawn from published or unpublished writings, either word-for-word or in paraphrase, have been clearly identified as such. Third parties were not involved in the drafting of the content of this dissertation; most specifically, I did not employ the assistance of a dissertation advisor. No part of this thesis has been used in another doctoral or tenure process.

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Article I

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SPECIAL FEATURE: ORIGINAL ARTICLE

Agroforestry for Sustainable Landscape Management

Exploring land-use histories of tree-crop landscapes: a cross-site comparison in the Mediterranean Basin

Franziska Wolpert[1] · **Cristina Quintas-Soriano**[1] · **Tobias Plieninger**[1,2]

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Abstract

Agroforestry landscapes in the Mediterranean Basin have emerged in a co-evolution between humans and nature and provide numerous ecosystem services to society. Tree crops are iconic elements of these landscapes and have frequently been managed in a sustainable way over centuries, shaping multifunctional landscapes and local people's cultural identities. However, many Mediterranean tree-crop landscapes are undergoing substantial land-use changes, threatening important ecosystem services as a result. The overarching goal of this study is to explore common and diverging patterns of land-use change across different tree crops (oaks, chestnuts, olives) and contrasting landscapes in the Mediterranean Basin over a 200-year period. Specifically, we aim to: (1) describe the dominant land-use change processes across these three crop types using three exemplary sites per crop; and (2) identify and classify the main drivers that determine these landscapes' land change histories. We find a general acceleration of landscape dynamics and identify expansion, continuity, polarisation, intensification, abandonment and renaissance as dominant processes. Although each landscape history is contextualised, we observe a general trend from multifunctional tree-crop landscapes (expansion) towards intensification or abandonment in the last 70 years. The landscapes of the southern fringe of the Mediterranean Basin show predominant trends towards intensification, while the northern landscapes evolve towards abandonment. The driving forces identified are diverse and interrelated, comprising sets of socio-cultural, political, technical, economic and natural factors. We offer some key lessons for sustainable landscape management in highlighting the undervalued potential of tree crops, the inherent complexity of landscapes, the interdependencies of drivers and the importance of economic and socio-cultural driving forces.

Keywords Agroforestry · Driving forces · Land management history · Landscape change · Tree crops · Sustainable landscape management

Introduction

The landscapes of the Mediterranean Basin are not only shaped by different climatic, topographic and geologic circumstances but are also strongly interconnected by human culture and common land management practices (Blondel 2006). Mediterranean landscapes have been described as complex and adaptive systems that co-evolve through human-nature interactions, creating the ecological as well as social foundations to provide multiple ecosystem services (Martín-López et al. 2016). Different types of land use as well as various management intensities create a mosaic of diverse landscape types and hence habitats for vast biodiversity (Blondel 2010, UNEP/MAP 2016). In particular, Mediterranean tree-crop systems maintain multiple ecosystem services compared to annual arable agriculture, which

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✉ Franziska Wolpert
franziska.wolpert@uni-kassel.de

[1] Faculty of Organic Agricultural Sciences, University of Kassel, Steinstraße 19, 37213 Witzenhausen, Germany

[2] Department of Agricultural Economics and Rural Development, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany

is disturbance-based and thus often associated with sustainability challenges such as high water run-off rates, net soil loss through erosion and/or nutrient and carbon losses (Crews et al. 2016; Martín-López et al. 2016). The Mediterranean Basin harbours iconic tree-crop landscapes that have been formed by traditional management over centuries (Grove and Rackham 2001). Characteristically, these landscapes consist of scattered trees with a diverse, grazed and/or cultivated understorey, which are often located on nutrient-poor and dry soils and are well-known for their species diversity (Olea and San Miguel-Ayanz 2006). The oak tree-crop landscapes of the Iberian Peninsula, called dehesas in Spain and montados in Portugal, are famous examples of such systems. Other landscape-shaping tree crops in the Mediterranean include pine nuts, chestnuts, beechnuts and olives (Grove and Rackham 2001). These systems are used to obtain multiple goods and services, including food, firewood, leaves and understorey as food for livestock and material for handicraft. Thus, tree-crop landscapes contribute in multiple ways to local people's well-being and play a key role in their cultural identity (Kizos and Koulouri 2006; Infante-Amate and Molina 2013).

In the last few decades, Mediterranean landscapes have frequently experienced polarisation in their development: on the one hand industrialisation and/or intensification of land management, for example through increased inputs of agrochemicals and mechanisation; and on the other hand abandonment of land, for example through the migration of rural people to urban areas (Jones et al. 2011). Both processes may lead to a loss of biodiversity and a decline in the provision of ecosystem services, including important cultural services such as cultural heritage or spiritual and aesthetic values (Bugalho et al. 2011; Plieninger et al. 2016). Sustainable landscape management (i.e. a holistic approach promoting a landscape's long-term capacity to provide a variety of ecosystem services) represents one major approach to addressing these pressures, and agroforestry especially has recently received growing scientific and policy interest as part of broader sustainable landscape management strategies (Plieninger et al. 2015; Sanz et al. 2017).

An important foundation of future-oriented landscape management strategies is a thorough understanding of past land-use systems (Antrop 2005; Black et al. 1998; Palang et al. 2005). In particular, a better knowledge of past tree-crop landscapes and their dynamics may offer inspiration for future decisions on Mediterranean land uses. Comparisons of historical approaches are increasingly used to inform landscape science and practice (e.g. Acha and Newing 2015). However, there is a research gap in cross-site comparisons to investigate landscape histories and the driving forces of landscape change over longer time frames (Frattaroli et al. 2014; Jepsen et al. 2015). Furthermore, knowledge about the complex interactions of socio-cultural, political, technical, economic and natural drivers remains scant (Bürgi et al. 2004; Plieninger et al. 2016). Therefore, this study aims to provide knowledge and insights into the complexity of landscape history. We analyse the landscape histories of the last 200 years for three key Mediterranean tree crops (olives, cork and chestnuts) in three contrasting Mediterranean landscapes. Our specific goals are to: (1) explore the history of change processes in tree-crop landscapes through the development of narratives; and (2) identify and classify the main drivers of change acting on these landscapes. Finally, we discuss and derive a series of key lessons for sustainable landscape management.

Methods

Tree crops in the Mediterranean region

We selected three iconic tree crops of the Mediterranean region that shape landscapes, represent important resources for human subsistence and have been sustained over a long time span, namely cork oaks (*Quercus suber*), chestnuts (*Castanea sativa*) and olives (*Olea europea*) (Fig. 1). These landscapes represent a wide range of land-use intensities and are closely interwoven with the socio-economic and cultural histories of the people living in these landscapes.

Cork oak is limited to the Western Mediterranean Basin (Stockwell 1947). The landscapes are characterised by widespread pastures with scattered oak trees, occurring either in pure stands or mixed with holm oaks (*Quercus ilex*). Cork oaks have been grown for multiple uses, but the main and most desirable product is the outer bark of the tree. It can be harvested every nine years and is regenerated in that time by the tree. Cork oak is adapted to poor and dry soil conditions but demands a lot of light and is therefore naturally replaced by other trees as soon as light becomes scarce (Grove and Rackham 2001).

Chestnuts are long-lived trees that are often landscape-forming. Their high yield and their nutrient composition facilitate their use as a staple food as an alternative to grain. Therefore, in many cultures chestnuts are referred to as 'bread trees' (Tagliaferri and Di Lonardo 2016). Their fruits are often used as food, their wood for construction and heating and the tannic acid they contain for tanning leather (Perry 1967).

Olives are assumed to be the most traditional tree crop in the Mediterranean Basin. In fact, the existence of olive trees was frequently used to define the border of the Mediterranean region. From antiquity to the present day, olive cultivation has been widespread and has shaped many cultural landscapes in this area (Cecchini et al. 2019). Olives have formed the basis of many people's livelihoods, most notably by providing olive oil (Kizos and Koulouri 2006).

Landscape and literature selection

For each crop, we chose three landscapes distributed across different countries and dominated by the respective crop. We selected these landscapes and the corresponding literature as follows. In the first step, we searched the Web of Science and Google Scholar databases for each tree crop in combination with the different Mediterranean countries (i.e. we searched for "chestnut" and "Spain") to identify potential case study landscapes in the countries of the Mediterranean Basin. We chose the landscapes to identify landscape change processes and driving forces and examined the suitability of available publications for that purpose. We selected the landscapes with the best availability of literature on landscape history as our case studies. In the second step, we used the same databases to search for the keyword combination "landscape" and "crop" (i.e. we searched for "chestnut" and "Corsica" and worked through the first 200 studies returned by Google Scholar and all studies found in the Web of Science). We complemented the findings with relevant literature from the previous search as well as by snowballing. We used the framework of driving forces (short: drivers) to describe the reasons behind landscape change (cf. Bürgi et al. 2004) and diligently selected four to six key papers to compile regional landscape histories. We prioritised publications by different authors over multiple publications by the same author but ultimately selected those publications with the most relevance. We chose contrasting landscape histories regarding the main processes and drivers and covered as many different countries and cultures as possible. To do so, we picked one Southern Mediterranean country and two Northern Mediterranean ones for each crop (Fig. 2). Given that literature for the southern fringe of the Mediterranean Basin was scant, we additionally conducted one expert interview (with university-based experts with profound knowledge of the particular crop and landscape) for each of the three landscapes. The case study regions for cork landscapes were Alentejo in Portugal, the Kroumerie-Mogod Mountains in Tunisia and Extremadura in Spain. The chestnut landscapes comprised Corsica in France, the Northern Apennines in Italy and the Aegean region of Turkey. For olive landscapes, we chose Lesvos in Greece, Baena in Spain and the Rif region of Morocco. Interpretations of the boundaries of each landscape were based on the information and spatial references of the primary publications. In our cases, the landscapes were either defined by administrative units or by natural borders (Table 1).

The focus of our research was on the landscape scale, but we considered drivers of different scales from local to global levels. We chose a time span from 1800 to the present, as this represents a relatively long time frame for which good evidence is available. Indeed, short time frames are disadvantageous because it is difficult to differentiate between parallel occurring drivers and their effects (Jepsen et al. 2015).

Landscape histories, processes and driving forces

We first compiled a model narrative for one of the landscapes. This template was then used to compile narratives for all nine study landscapes (see Supplementary Material). Once these were written and harmonised among each other, we started a more systematic approach of classifying changes into processes and categorising drivers. For each landscape and period, we synthesised the main process and the main driving forces behind it and compiled a summary of each of the landscape narratives.

A landscape process is defined here as the time period in which the landscape (shaped by a tree crop) undergoes a specific prevalent process related to the main crop. For example, if the extent of the chestnut landscape increases on Corsica, the landscape process of Corsica in that time period is "expansion". We must emphasise that a landscape does not exist as a fixed state, but rather is always in a co-evolving process of humans and nature and therefore can be defined as a "process". The turning point from one "process" to another is the moment at which there is a shift in the prevalence of the process. We illustrated the

Fig. 1 Examples of tree-crop landscapes in the Mediterranean Basin. Left: Cork oak landscape in Alentejo, Portugal (picture by Tobias Plieninger); Centre: Chestnut landscape in the Northern Apennines, Italy (picture by Johannes Schantl); Right: Olive landscape in the Rif region of Morocco (picture by Tobias Plieninger)

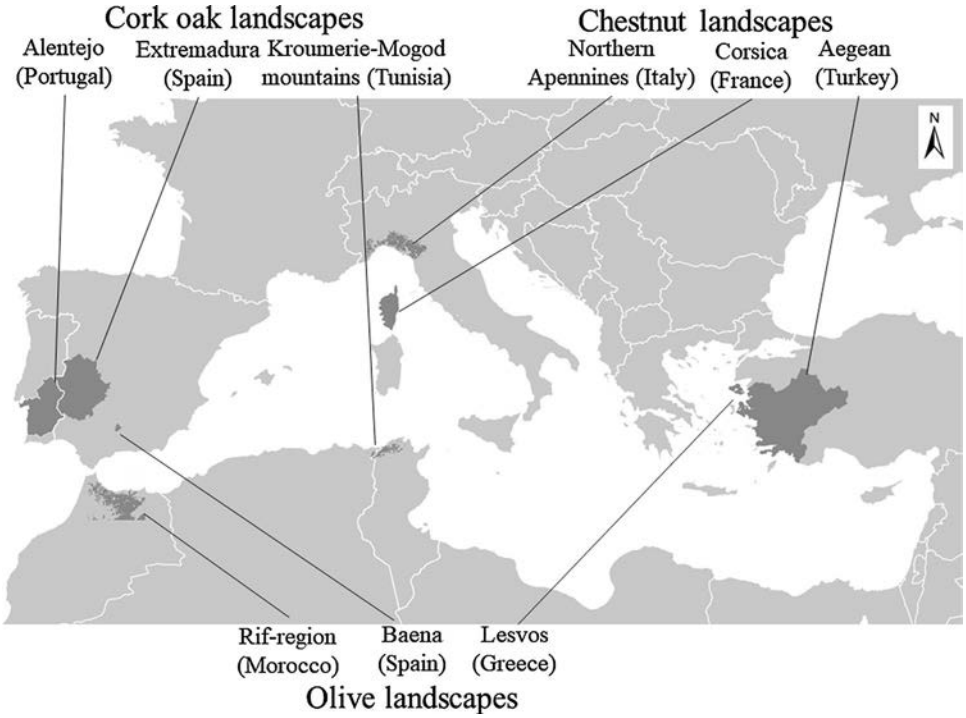

Fig. 2 Location of the nine tree-crop landscapes across the Mediterranean Basin

landscape processes in a timeline to explore differences as well as common patterns across distinct landscapes.

For each landscape process, we extracted the driving forces and depicted them in a table. We used five categories of drivers: socio-cultural, technical, political, economic and natural (modified from Bürgi et al. 2004). For each of the six landscape processes, we evaluated the proportional contribution of each category of driving forces to the process. As an example, we considered all processes of "abandonment" across all landscapes and examined the proportion of natural driving forces compared to the other categories. This enabled us to ascertain whether there was any pattern in the distribution of drivers regarding the processes. The results are displayed in the following ways: (a) short summaries of the nine landscape histories; (b) systematic comparison of the change processes in different periods; and (c) systematic comparison of the driving forces of landscape change.

Results

Nine comprehensive narratives of tree-crop landscape histories serve as the basis for the compiled narratives summarising the main processes and driving forces of landscape change (Supplementary Material).

Tree-crop landscapes

Cork oak cultivation

Cork oak in Alentejo, Portugal Before 1820, cork oaks did not play a major role for people in Alentejo. From the 1820s to the 1950s, the cork oak landscape (called *montado*) underwent a period of expansion, promoted by the liberalisation of the markets. Multiple demands on the use of cork landscapes and new technological advancements in the cork processing sector enhanced the profitability of the *montados* for land managers. At this time, the *montados* shaped people's cultural identity. In the period from 1950 to the present, there was a polarisation of land use in the cork oak landscape: market liberalisation and the resultant decline in profitability led to the abandonment of less productive sites, whereas the most productive sites were cultivated even more intensively. These developments were additionally fostered by the use of agrochemicals and the over-exploitation of the landscape. A labour shortage due to outmigration further accelerated this evolution. In particular, in recent years droughts and pests have applied further pressures on the cork oak landscapes.

Cork oak in Extremadura, Spain Cork oak landscapes constitute a traditional form of land use in Spain and have been used for multiple goods as a major source of livelihoods.

In the period from the 1800s to the 1950s, the cork oak landscape of Extremadura expanded. Among other reasons, the turmoil that resulted from the Napoleonic Wars and the associated abandonment of the pastures facilitated cork oak's expansion in south-western Spain, as the absence of livestock allowed young cork oaks to become established. Moreover, the over-exploitation of other crops like vines leached the soil and necessitated the use of less demanding crops like cork. The rising demand for cork combined with market liberalisation increased the profitability of cork production in the second half of the nineteenth century. Population growth as well as a privatisation wave further fostered this evolution in the first half of the twentieth century. However, the situation changed from the 1950s to the 1990s with the polarisation of land use, primarily driven by industrialisation (e.g. the input of agrochemicals) and the related loss of profitability of traditional production. During this period, fertile areas were intensified and often converted to intensive agricultural croplands, whereas steeper and unfertile areas were abandoned. Outmigration led to even greater polarisation. However, agricultural subsidies supported cork production and some conservation measures prohibited tree felling which, despite some considerable losses, ultimately saved vast areas of cork oak landscape. The renaissance of the cork oak landscape began in the 1990s and is still taking place today. It has been driven by conservation programmes that support the traditional management and replanting of oak trees. Nowadays, new marketing strategies, such as the labelling of "organic agriculture" or a "protected designation of origin", further enhance the profitability of other landscape products like ham while contributing to multifunctionality.

Cork oak in the Kroumerie-Mogod Mountains, Tunisia Tunisia's cork oak history is rather young: cork oak landscapes were planted around 1860 and were first harvested in the 1880s. The land covered by cork oak (and therefore also the exploited cork) is state-owned. Nevertheless, these landscapes have offered multiple goods and subsistence to locals. The 1930s until the 1950s saw the intensification and the over-exploitation of the cork landscape, driven by new government restrictions on what was previously free utilisation (e.g. of firewood) by locals. These restrictions as well as droughts threatened local livelihoods and led to the disregard of these laws. Since the 1950s, there has been an ongoing decline of cork oak landscapes, mainly driven by population increase connected with over-exploitation, which has prevented tree and grass regeneration. Given that locals are allowed to engage in grazing, there has been an ongoing conversion to treeless rangelands. Furthermore, natural forces like droughts and fire have played a major role as driving forces of abandonment.

Chestnut cultivation

Chestnuts in Corsica, France In Corsica, chestnuts have not only represented a natural resource for multiple purposes and a key component of local livelihoods, but also an important part of cultural identity, expressed for example through the traditional craft products developed by local people. French rule aimed to defame chestnuts as a staple food. It labelled chestnut as "the food of laziness" and restricted chestnut growing to undermine Corsicans' quest for independence. However, this restriction did not stop the cultivation of chestnuts and ultimately made Corsicans more aware of their independence from global food systems. Chestnut cultivation became a symbol of resistance and Corsican freedom. From the 1850s, the chestnut culture collapsed and chestnut cultivation was increasingly abandoned for multiple reasons. One driver was the changing lifestyle of the people on the French mainland and the desire of Corsicans to adapt to this. An outmigration wave commenced, resulting in Corsicans migrating to the French mainland and other European countries. World War 1st and 2nd led to worker shortages for the harvest season. In addition, chestnut diseases (mainly chestnut blight and ink disease) reduced the number of chestnut stands, while economic profitability suffered from the opening up of the market and resultant greater competition. During the 1980s, the chestnut landscape began to undergo a period of renaissance, driven by local initiatives that revived the chestnut culture and the related economy, buttressed by technological progress in processing (e.g. shell-opening machines). To date, there have been tensions between the aim of multifunctional and diverse traditional systems and less diverse, economically more profitable production systems, the former often being more labour-intensive.

Chestnuts in the Northern Apennines, Italy Traditional culture in the Northern Apennines has been closely linked to chestnut cultivation as a staple crop. The entirety of the nineteenth century was a period of the expansion of chestnut cultivation, driven by population growth. In this region, chestnuts were grown for multiple uses (e.g. food, fodder for animals, heating) within subsistence agriculture, but also constituted a profitable trading good. From the 1900s until the present day, a period of abandonment of the chestnut landscape emerged, driven by multiple forces. Increasing pest pressure and hence high tree damage and yield losses have led to a reduction in profitability. Simultaneously, the changing lifestyle of the local population has led to outmigration and a loss of interest in chestnut cultivation. In the last decade, the preservation of local knowledge about chestnut management and the prevalence of cultural connections to chestnuts as well as rising consumer interest have given hope for a renaissance of the chestnut culture and landscape.

Chestnuts in the Aegean region, Turkey From ancient times up to the middle of the twentieth century, chestnut landscapes prospered in the Aegean region of Turkey. They contributed as a profitable good to locals' livelihoods for multiple purposes, such as by constituting an importance source of food, timber and honey. However, since the beginning of the twenty-first century, the land use of chestnut stands became polarised across the region. The demand for chestnuts in Turkey was higher than the supply, but it was risky to plant traditional chestnut trees that are not resistant to widespread diseases. High demand for chestnuts led to a transformation of chestnut landscapes to industrial production as well as the abandonment of marginal areas owing to a lack of profitability. To control the diseases that were threatening chestnut cultivation, the state restricted the management of chestnuts to local people in nature reserves. However, this prevented people from removing infested trees, which enhanced the spread of the disease problems and further instigated abandonment. Although local people have increased the sustainability of chestnut stands by developing small-scale agriculture and fostering tree health, more work-intensive, small-scale agriculture is no longer profitable because of the competition posed by global markets. This presents an uncertain future for the conservation of these landscapes.

Olive crop landscapes

Olives on Lesvos, Greece On the Greek island of Lesvos, olive cultivation expanded from 1800 until the 1920s. At this time economic development and population growth combined with high demand for olive oil promoted olive cultivation. Technological developments in the transport sector supported this evolution, meeting overseas demand. An intensification process of olive land use started in the 1920s and persisted until the 1970s. It was driven by an economic crisis and associated outmigration to the mainland. Unlike other land uses (e.g. annual crop cultivation), olive production remained in demand and profitable. However, the use was specialised on olive oil production instead of multiple demands. Since the 1970s, olive cultivation is no longer profitable. Therefore, there has been an ongoing abandonment process, driven by the low profitability of olive cultivation and reinforced by an economic crisis, outmigration and a lack of appreciation of farming related to a changing lifestyle. However, this process has been somewhat offset by the cultural connectedness of farmers to their olive trees, continuing to grow them despite their uncertain profitability.

Olives in Baena, Spain In the period 1800–1820, olive growing continued as before, representing an aspect of local livelihoods and an important tree species within diverse agroforestry systems. From the 1820s to the 1930s, olive cultivation was intensified and expanded simultaneously. This process was fostered by the liberalisation of global markets and a resulting economic crisis. Olives were valued for their versatility (e.g. table olives, olive oil, fodder for animals, wood) as well as general demand in global markets, increasing their profitability. These developments were further reinforced by the privatisation of land, population growth and the mechanisation of land management. In the period from 1936 to 1975, the disorder of the Spanish Civil War led to the temporary abandonment of olive cultivation. From 1975 until the present day, there has been a second wave of intensification and expansion of olive cultivation, bringing large-scale olive monocultures to the contemporary landscape of Baena with a particular emphasis on olive oil production. This process has been driven by high demand for olive oil and the considerable profitability of olive cultivation, reinforced by subsidies. Mechanisation and the input of agrochemicals have also increased in recent decades.

Olives in the Rif region, Morocco As a staple food source, olive landscapes have continuously contributed to the livelihoods of local people in the Rif region of northern Morocco. In this region, olives have been used for multiple purposes, such as for fruit consumption, oil, wood harvesting for heating and as a fodder source for livestock. From the 1910s, olive cultivation expanded due to the privatisation of land and as people converted forests into olive agroforestry systems, fearing that political will would transform their forests into state- or public-owned land. From 1956 the olive landscape of northern Morocco underwent a process of intensification. The main driving force was the global demand for olive oil and the Moroccan government's running and financing of programmes to enhance olive production to supply global markets. However, industrialisation and the specialisation on olive oil production have engendered various problems, such as vitality losses of olive trees and lower productivity, for example the fact that tree nurseries cut the tap-roots, which does not allow the trees to reach groundwater.

Processes of landscape change

We have identified and characterised six distinct processes of change in the chosen Mediterranean landscapes:

- *Expansion*. A tree-crop landscape that is flourishing and growing in its extent as well as in its importance for human use.
- *Continuity*. A landscape that is not significantly changing but rather remaining in the same state over a period of time. The tree crop is either still one of many trees or

already enjoys a certain level of importance, depending on the landscape.

- *Polarisation*. Concurrent processes of abandonment on less fertile, steeper places as well as intensification on fertile zones.
- *Abandonment*. A tree-crop landscape that is undergoing a process of decreasing inputs as well as outputs.
- *Intensification*. A tree-crop landscape whose management has resulted in an increased yield per area. This often but does not necessarily coincide with an intensified use of industrial inputs, such as machinery and agrochemicals.
- *Renaissance*. The process of returning to expansion following a phase of abandonment, intensification or polarisation.

Figure 3 shows the different processes for each of the nine landscapes between 1800 and the present. A general trend that has been observed was an increased dynamic in land change processes in the last century compared to previously. It is noteworthy that in all landscapes, sooner or later there was a time of expansion. However, this process was interrupted by either abandonment, intensification or both (polarisation) between 1850 and 1970. Recently, the cork landscape in Extremadura and the chestnut landscape in Corsica have evolved towards renaissance.

Driving forces

Table 2 shows the main driving forces for each period in which a certain process has proved prevalent in each of the nine landscapes. Some drivers have repeatedly led to particular processes. The profitability of the crop for land managers, population growth, multiple demands for tree uses (e.g. food, timber, fodder), being a part of local livelihoods and shaping cultural identities have represented the main drivers of expansion. However, uncommon reasons for the expansion of a tree-crop landscape have also emerged, such as in Morocco, where political reforms and community decisions have led to the expansion of the olive landscape, even though most people would prefer a landscape with more diverse agroforestry systems.

Pests and diseases stand out as a very severe driver as they have always been accompanied by reduced profitability or an economic crisis and have mainly affected chestnut landscapes. While population growth has often seemed to be a driver of expansion, outmigration has typically led to the abandonment. Missing profitability, agrochemicals, market liberalisation, outmigration, pests and diseases as well as land-use restrictions have proved to be the main drivers of polarisation. The simplification of land use has often led to a process of intensification, but it can also drive abandonment. Most processes have been driven by multiple interrelated factors, although for some only a few or even just one driving force has been responsible (e.g. the abandonment of the olive landscape in Spain was the result of the Civil War). Counterintuitively, war may lead to a rise (expansion) and a fall (abandonment) of a landscape, as seen for the olive landscape in Baena, Spain (abandonment) and the cork oak landscape in Extremadura, Spain (expansion).

We can allocate the driving forces into five categories: socio-cultural, political, technical, economic and natural. The socio-cultural category contains the highest number of individual drivers, followed by political and economic drivers. Natural and technical drivers present a smaller number of individual drivers (Table 3).

For each of the six landscape processes (i.e. expansion, continuity, polarisation, intensification, abandonment, renaissance) we may depict the proportional contribution of the driving force categories to the process of landscape change (Fig. 4). Socio-cultural drivers have played a major role across the six landscape processes. This is particularly the case for continuity, expansion and abandonment. Technical drivers have not emerged as drivers for continuity and abandonment, whereas natural driving forces only contribute to abandonment, polarisation and intensification.

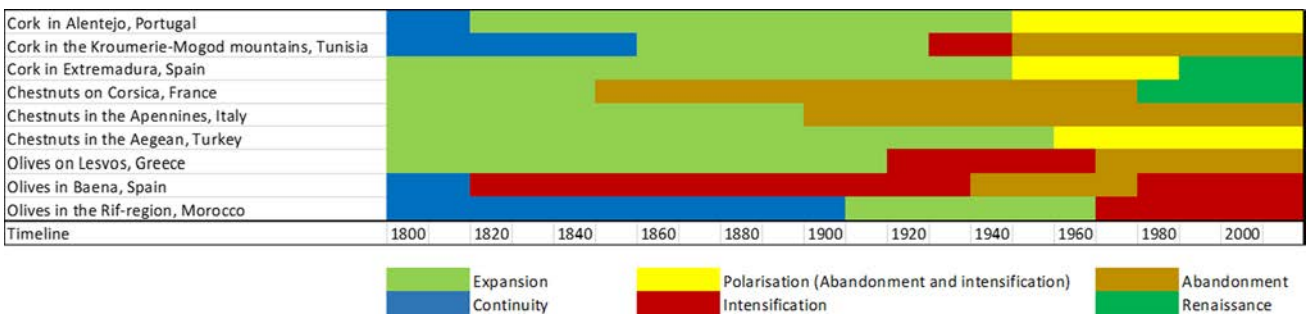

Fig. 3 Historical periods of the nine tree-crop landscapes from 1800 until present

Table 1 Tree-crop landscape features and key publications used

Crop type	Landscape	Landscape boundaries	Extent (km^2)	Tree crop cover	Population density (inh./km^2)	Ownership structure	Landscape formation	Key publications
Cork	Alentejo (Portugal)	Administrative unit	31,550	In some regions the *montados* are dominated by cork oak	22.5	Large estates, privately owned	Lowlands	Costa et al. (2009), Fonseca (2003), Jones et al. (2011), Muñoz-Rojas et al. (2019), Pinto-Correia and Mascarenhas (1999) and Pinto-Correia et al. (2019)
	Kroumerie-Mogod Mountains (Tunisia)	Mountain range	n.a	Dominating tree species	about 130	State-owned	Mountains	Campos et al. (2007, 2008, 2014), Zapata (2009) and Mansoura et al. (2001)
	Extremadura (Spain)	Administrative unit	41,634	In some regions the *dehesas* are dominated by cork oak	25.6	Large estates, privately owned	Lowlands	Guzmán Álvarez (2016), Grove and Rackham (2001), Kizos and Plieninger (2008), Stockwell (1947) and Vicente and Alés (2006)
Chestnut	Corsica (France)	Island	8,882	Dominant tree on major part of the island	38.6	Small-scale, privately owned	Mountains	Michon (2011), Mouillot et al. (2005, 2008), Perry (1967) and San Roman Sanz et al. (2013)
	Northern Appenines (Italy)	Mountain range	n.a	Dominant tree on wide parts of the mountains	n.a	Small-scale, privately owned	Mountains	Agnoletti (2007), Avanzato (2009), Buonincontri et al. (2015) and Pezzi et al. (2011, 2017)
	Aegean region (Turkey)	Administrative unit	90,456	In some parts dominantly cultivated	110	n.a	Mountains	Avanzato (2009), Bozoglu et al. (2019), Serdar et al. (2014) and Wall et al. (2019)
Olives	Lesvos (Greece)	Island	1,632	Dominant tree on wide parts of the island	53	Small-scale, privately owned	Mountains	Kizos and Koulouri (2006, 2010), Kizos et al. (2010), Marathianou et al. (2000) and Zagaria et al. (2017)
	Baena (Spain)	Administrative unit	362	70% of land surface	53.2	Large estate, company-owned	Lowlands	Infante-Amate (2012a, b), Infante-Amate and Molina (2013) and Infante-Amate et al. (2016)
	Rif region (Morocco)	Mountain range	n.a.	Increasingly dominating	n.a	Small-scale, privately owned	Mountains	Aumeeruddy-Thomas et al. (2017), Daoui and Fatemi (2014), Kholy (2012) and Kmoch et al. (2018)

n.a. information not available, *inh.* inhabitants

Table 2 Main driving forces for each process of landscape change for the nine tree-crop landscapes

	Processes	Time	Socio-cultural	Political	Technical	Economic	Natural
Cork landscapes							
Alentejo, Portugal	Continuity	1800–1820s				Low demand for crop	
	Expansion	1820s–1950s	Multiple demands, cultural identity	Market liberalisation	Technological progress	profitability	
	Polarisation	1950s–present	Over-exploitation, outmigration	Market liberalisation	Agrochemicals	Missing profitability	Pests or diseases, drought
Kroumerie-Mogod Mountains, Tunisia	Continuity	1800–1860s	n.a				
	Expansion	1860s–1930s	Livelihoods, multiple demands				
	Intensification	1930s–1950s	Over-exploitation	Land-use restrictions			Drought
	Abandonment	1950s–present	Over-exploitation, population growth, specialised demand	Land-use restrictions			Drought, fire
Extremadura, Spain	Expansion	1800–1950s	Livelihoods, multiple demands, population growth	War, privatisation of land, market liberalisation		Demand for crop, profitability	
	Polarisation	1950s–1990s	Outmigration	Agricultural subsidies, land-use restrictions	Agrochemicals	Missing profitability	
	Renaissance	1990s–present		Conservation programmes		Profitability, marketing strategy	
Chestnut landscapes							
Corsica, France	Expansion	1800–1850s	Livelihoods, multiple demands, cultural identification, community decisions	Land-use restrictions			
	Abandonment	1850s–1980s	Outmigration, changing lifestyle	War, market liberalisation		Economic crisis	Pests or diseases
	Renaissance	1980s–present	Community decisions, awareness		Technological progress		
Northern Apennines, Italy	Expansion	1800–1900s	Livelihoods, multiple demands, population growth			Profitability	
	Abandonment	1900s–present	Outmigration, changing lifestyle			Missing profitability	Pests or diseases
Aegean region, Turkey	Expansion	1800–1960s	Livelihoods, multiple demands			Profitability	
	Polarisation	1960s–present		Market liberalisation, land-use restrictions	Mechanisation, agrochemicals	Demand for crop, missing profitability	Pests or diseases
Olive landscapes							

Table 2 (continued)

	Processes	Time	Socio-cultural	Political	Technical	Economic	Natural
Lesvos, Greece	Expansion	1800–1920s	Population growth		Technological progress	Demand for crop, economic growth	
	Intensification	1920s–1970s	Specialised demand, outmigration			Demand for crop, profitability, economic crisis	
	Abandonment	1970s–present	Outmigration, changing lifestyle			Missing profitability, economic crisis	
Baena, Spain	Continuity	1800–1820s	Livelihoods, multiple demands				
	Expansion/intensification	1820s–1936	Multiple demands, population growth	Privatisation of land, market liberalisation	Mechanisation	Demand for crop, profitability, economic crisis	
	Abandonment	1936–1975		War			
	Expansion/intensification	1975–present		Agricultural subsidies	Mechanisation, agrochemicals	Demand for crop, profitability	
Rif region, Morocco	Continuity	1800–1910s	Livelihoods, multiple demands				
	Expansion	1910s–1950s	Community decisions	Privatisation of land			
	Intensification	1950s–present	Specialised demand	Land development plans		Demand for crop	

n.a. information not available

Table 3 Categorisation of drivers of landscape change

Type of drivers				
Socio-cultural	Political	Technical	Economic	Natural
Over-exploitation	Land development plans	Technological progress	Low demand for crop	Pests or diseases
Livelihoods	War	Mechanisation	Demand for crop	Drought
Multiple demands	Privatisation of land	Agrochemicals	Missing profitability	Fire
Specialised demand	Market liberalisation		Profitability	
Population growth	Land-use restrictions		Marketing strategy	
Outmigration	Agricultural subsidies		Economic crisis	
Changing lifestyle	Conservation programmes		Economic growth	
Cultural identification				
Community decisions				
Awareness				

Discussion

While sustainable landscape management is a forward-looking planning practice, considerable knowledge can be derived for sustainability by focusing on past landscape evolutions. From 1800 to the present, the Mediterranean landscapes analysed in this study generally evolved from expansion towards either abandonment or intensification and showed increased spatial and temporal dynamics. Our results (Fig. 3) show common patterns among the crops: Olive systems tended to be intensified, chestnut systems were generally abandoned and cork was rather polarised between intensification and abandonment in the last 70 years. The landscapes in the northern fringe of the Mediterranean Basin have shown a tendency of abandonment due to outmigration from rural areas. The decline of agricultural population is a typical phenomenon of the northern Mediterranean fringe (Benoit and Comeau 2005). By contrast, the landscapes of the southern fringe have faced considerable population pressure. The driving forces behind these landscape changes are diverse. However, they can be categorised into socio-cultural, political, technical, economic and natural drivers. Remarkably, socio-cultural drivers have played a major role in most land-use change processes.

Besides the individual landscape histories and their driving forces, a pattern can be discerned in most of the landscape histories: The landscapes faced multiple demands, by being (for instance) sources of food, fodder and wood, rendering them an important part of local people's livelihoods. During the course of the nineteenth and especially the twentieth centuries, there was a substantial decline in traditional land uses due to the overall industrialisation of agriculture (mechanisation, agrochemicals) and the reduced profitability of traditional systems, resulting in either intensification or abandonment. However, local people's cultural associations and initiatives have emerged, valuing cultural heritage and contributing to its recovery. A similar history has been identified for other tree crops, such as in almond landscapes in the Apennines in Italy by Frattaroli et al. (2014).

Landscape processes

We have noted a common trajectory from an expanding, multifunctional landscape towards either intensified or abandoned systems, similar to Pinto-Correia and Vos (2004). This polarisation has largely occurred due to market liberalisation and the related competition among goods. Market liberalisation in most cases has brought about a loss of profitability, due to the presence of competition among suppliers from different contexts, such as climatic and soil conditions, labour costs and political restrictions. However, in the case of cork oak cultivation, which is only distributed in the Western Mediterranean region, market liberalisation has had a positive effect, especially because a product like cork can neither be produced in a different climate nor in a more industrialised production system.

Our landscape histories demonstrate the overall increased dynamics of landscape processes in the second half of the studied period, as additionally observed by Jepsen et al. (2015). This may partly be an artefact due to a lack of documentation in the past, but also an expression of an actual increase in land-use dynamics. We have found that in most cases the transition from one process to another was not aligned among different landscapes. The land-use regimes of the European case studies show more homogeneous patterns of change from one regime to the next. We assume that we can cover more individual trajectories at a landscape scale compared to a national scale (Jepsen et al. 2015). There may also be distinct time lags between land-use regimes and actual visibility in the different landscapes.

The common trajectory of a trend towards polarisation can be broken down into trends among the different tree-crop

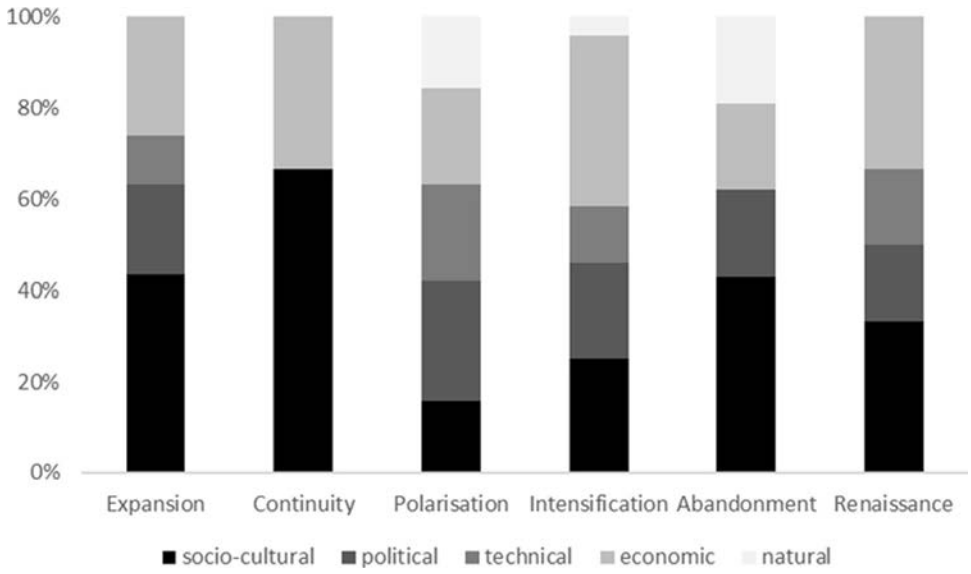

Fig. 4 Driving forces that shape the processes of landscape change. The *y*-axis refers to the percentage of drivers contributing to the processes of land-use change

landscapes for olives, chestnuts and cork oaks. The main process of chestnut landscapes in the nineteenth century was expansion, as chestnut culture has a long and widespread history (Avanzato 2009), while the importance of olives and cork mainly developed in the twentieth century. In olive landscapes, intensification has been a prevalent process over the last 70 years, driven by the combination of high demand for olive oil and the fact that olives can be grown in intensified systems (cf. the olive landscape in Baena). By contrast and despite high demand, chestnut systems have been largely abandoned over the past century, primarily due to diseases. Cork landscapes have exhibited especially polarised land-use patterns (i.e. intensification and abandonment). Such polarisation of cork landscapes in Portugal and Spain has in both cases been driven by the overall industrialisation of agriculture and hence the intensification of more profitable sites as well as the abandonment of marginal sites. The driving forces behind the process of abandonment of the Tunisian cork landscapes have been governmental land-use restrictions aimed at counteracting over-exploitation.

We can see a tendency of the landscape processes in the northern fringe of the Mediterranean Basin to move towards abandonment and renaissance. Abandonment has occurred in the olive landscape on Lesvos as well as the chestnut landscapes in the Northern Apennines due to the outmigration of local people. Renaissance has been observed in the case of the cork oaks in Extremadura and the chestnuts in Corsica owing to regained profitability, but also awareness and conservation programmes. The cork oak landscape in Alentejo has undergone a process of polarisation, whereas the olive landscape in Baena fails to fit this pattern. Indeed, this landscape represents a very special case as it is the only one that has undergone expansion and intensification simultaneously and that also did not start as a cultural landscape. The landscapes of the southern fringe have generally been focused on intensification, buttressed by a rising demand for food due to a rapidly growing population (Benoit and Comeau 2005; Zdruli 2014). We can observe intensification in the olive landscape of Morocco and polarisation in the chestnut landscape of Turkey. The abandonment process in Tunisia can be understood if the context is considered: high population pressure has led to over-exploitation, resulting in local people's restricted use and hence abandonment.

Driving forces of landscape change

We have found that most of the landscape processes are influenced by multiple interrelated driving forces that can be categorised as socio-cultural, political, technical, economic and natural.

Socio-cultural factors are important drivers of change and are essential for expansion and renaissance to occur. Similarly, a review of driving forces of landscape change across Europe has identified cultural drivers as a key reason for rural development activities (Plieninger et al. 2016). Multiple demands for the use of a tree-crop landscape are tending to lead landscapes towards expansion. However, the opposite trend—the intensified exploitation of a single crop—has led to landscape simplification. Socio-cultural drivers enjoy considerable importance in landscape management because they are prevalent in all landscape processes and usually play the dominant role. However, there is no evidence of their actual proportional contribution to decision making, which might, therefore, be investigated in future research via interviews regarding people's perceptions.

Political drivers do not only influence the legal frame in which a landscape develops but also directly determine profitability for land managers through subsidies (cf. Table 2).

Agricultural subsidies are usually named among the political drivers and have contributed to both intensification and abandonment. Land-use restrictions also play an important role and seem to instigate polarisation. This is supported by the European review on driving forces, where political drivers have appeared most often as a driver for intensification and represent the second-most common driver of abandonment (Plieninger et al. 2016).

In terms of technical driving forces, agrochemicals emerged most often, followed by mechanisation and technological progress, indicating an industrialisation of agriculture. Technical drivers seem to enjoy considerable importance in the case of polarisation of a landscape, but surprisingly no technical drivers were found to lead to abandonment. However, indirectly the technical opportunities for industrial intensification fostered the abandonment of less productive and particularly steeper slopes that cannot be managed as mechanised systems (Lasanta et al. 2017; Strijker 2005).

Economic drivers, in particular profitability or missing profitability, represent major drivers of landscape management, as it is necessary for people to make an income from the land. Therefore, missing profitability mostly leads to abandonment, whereas profitability fosters expansion, intensification and renaissance. The demand (or low demand) for a crop is closely connected to its profitability, as the two rise or fall together.

In general, natural drivers rarely appear, but within these, pests or diseases and droughts are prominently mentioned in the literature included within this study. Natural drivers play an important role in processes of abandonment and polarisation but not for expansion and scarcely for intensification. They mainly reflect negative aspects such as catastrophic events. Pests and diseases are very influential, especially for chestnuts. Traditional chestnut landscapes consist of pure *Castanea sativa* trees that are not resistant to diseases like chestnut blight, whereas *Castanea sativa* that is interbred with *Castanea crenata* and/or *Castanea molissima* can show resistance (Ramos Guedes-Lafargue et al. 2005). Pests and diseases determine the yield and thus people's livelihoods as well as the profitability of land management.

What is the future of Mediterranean landscapes?

Today, external shocks seem to be on the rise: the pressures posed by pests have increased due to globalisation and landscape simplification (Roossinck and García-Arenal 2015; Rusch et al. 2016), the prices of cork, chestnut and olive products are dependent on the world market and extreme weather events are expected to increase in magnitude and frequency, including droughts in the Mediterranean Basin (Beniston et al. 2007). Most contemporary forms of land use are unsustainable, as they are unable to maintain the multiple societal values of Mediterranean landscapes, such as biodiversity, food security, wood, aesthetic value and recreation for future generations (McIntyre 2008; Kremen et al. 2012). Our landscape histories demonstrate that tree-crop landscapes have met many of these needs in the past and seem to have considerable potential to meet current and future challenges (Hernández-Morcillo et al. 2018; Howlett et al. 2011). In fact, most of the renaissance activities in the tree-crop landscapes have been driven by cultural values such as tourism, outdoor recreation or sense of place. Nevertheless, these often fail to lead to increased profitability for land managers (Flinzberger et al. 2020). With the Mediterranean Basin being heavily affected by climate change, tree-crop landscapes may offer manifold adaptation and mitigation options, in addition to the cultural values they provide. Thus, finding the right financial instruments that would present incentives to land managers to support multifunctional tree crops represents the key to sustainable land management (Hernández-Morcillo et al. 2018). However, considering the increasing pressures, traditional systems that are typically centred on one dominant tree species may be at risk under changing climatic conditions. Introducing a mix of profitable tree-crop species as a crucial component of agroforestry systems (e.g. combined with pastoralism) may offer a way forward towards sustainability. Such traditional and novel systems should be sophisticatedly designed and carefully managed for diversity, profitability and multifunctionality. Emerging questions are: how can the attractiveness of sustainable landscape management be enhanced for locals? And which will be the incentives supporting this?

Limitations

Our study has covered some of the most iconic tree crops that shape landscapes and are important for human livelihoods in the Mediterranean region. We have utilised a novel approach to analyse and compare the processes and drivers of tree-crop landscapes, hence some limitations of our method need to be considered. We selected three important tree crops that occur at the landscape scale in the Mediterranean region, but other tree crops, for example pine nuts or almonds (Salas-Salvadó et al. 2011), have yet to be considered. Akin to other studies of landscape history (Frattaroli et al. 2014; Turner et al. 2018), published material on the historic development of our study landscapes remains limited, especially as regards those landscapes in the Middle Eastern and North African part of the Mediterranean Basin. Even if there are no natural risks named in certain periods, this does not necessarily mean the absence of these drivers. The authors of the literature that we used could have regarded them as not relevant for their publication. In particular, there is scant information available on the periods of continuity. Furthermore, there may be an inherent

trade-off between our wish to generalise findings across time and space and the consideration of the complexity of these landscape histories. This complicates the unravelling of processes, driving forces, challenges and solutions of the system (in this case the landscape) because there are many interdependencies across scales (Muñoz-Rojas et al. 2019). Given that our study has been based on a review of primary literature, biases in the identification of relevant drivers of change or in the assessment of processes in primary sources will have translated into similar biases in our study. Furthermore, our cross-site comparative approach has implied that we could not use literature published in local languages (with the exception of Spanish), potentially presenting another source of bias. Especially for the southern fringe of the Mediterranean Basin, there is little English language information about landscape history available. We attempted to reduce these biases via triangulation between different sources concerning each study landscape and by performing additional interviews with local landscape experts.

Conclusions

Global challenges raise the question of and the need for sustainable landscape management, with agroforestry likely to play a key role. In this study, we have found that many landscapes across the Mediterranean Basin have a long history of biodiverse and sustainable tree-crop systems, although they have undergone substantial changes over time. Our analysis of nine tree-crop landscapes in the Mediterranean Basin offers the following key lessons for future sustainable landscape management:

- Landscape history enables us to learn lessons for future sustainable landscape management. It points to the inherent complexity of landscapes, which must be embraced to guide land uses towards greater sustainability.
- Driving forces mostly appear in bundles and interdependencies across natural, political technological, sociocultural and economic factors, calling for a multi-sectorial and holistic approach to landscape management. However, in some cases single drivers, such as political restrictions or civil strife, can transform landscapes and may require particular attention.
- Profitability is a key driver for the existence and the persistence of tree-crop landscapes.
- Cultural and social drivers play an important role for landscape management, but they have not always been fully acknowledged.
- Tree-crop histories present considerable potential for multifunctional and diverse systems to cope with future challenges, compared to forestry or annual cropping systems.

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Article II

Collaborative agroforestry to mitigate wildfires in Extremadura, Spain: land manager motivations and perceptions of outcomes, benefits, and policy needs.

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Collaborative agroforestry to mitigate wildfires in Extremadura, Spain: land manager motivations and perceptions of outcomes, benefits, and policy needs

Franziska Wolpert · Cristina Quintas-Soriano · Fernando Pulido · Lynn Huntsinger · Tobias Plieninger

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Abstract Wildfires are increasing in severity, and magnitude in the Mediterranean Basin in recent years, reaching a yearly average of 450 000 ha over the last decade. Drivers include climate change, land-use change, and land abandonment. Wildfire mitigation requires landscape-level action as impact to each parcel is affected by the conditions of the others. We conducted a case study of a regional-level initiative that develops community efforts to mitigate wildfires through silvo-pastoral agroforestry systems, using an *integrated landscape management* approach. This approach involves collaboration among stakeholders to achieve multiple objectives. In order to derive insights into its potential, we asked participating land managers: (1) What motivates their participation?, (2) How do they perceive initiative outcomes?, and as urban outmigrants with non-traditional goals are increasing in rural areas, (3) Do responses differ between rural and neo-rural participants? Our results show that managers feel highly affected by wildfires and are strongly motivated to reduce wildfire risk. Land abandonment and inappropriate policy were major concerns. The initiative was seen to have positive outcomes for individual participants as well as the region, and to stimulate community connectedness. We conclude that fit to local contexts, integrated landscape management can be a well-received approach to reducing wildfire risk. Agroforestry systems in Extremadura can act as "productive fuelbreaks" that reduce fire risk over extensive areas, while restoring traditional landscapes. We suggest that programs to reduce wildfire risk can also be used as a leverage point for financing rural revival and provision of multiple ecosystem services.

Keywords Productive fuelbreaks · Wildfire mitigation · Mediterranean · Silvopastoralism · Agroforestry · Land abandonment · Integrated landscape management

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F. Wolpert (✉) · T. Plieninger
Faculty of Organic Agricultural Sciences, University of Kassel, Steinstraße 19, 37213 Witzenhausen, Germany
e-mail: franziska.wolpert@uni-kassel.de

C. Quintas-Soriano
Biology and Geology Department, Andalusian Center for the Assessment and Monitoring of Global Change (CAESCG), University of Almeria, Almería, Spain

F. Pulido
Institute for Dehesa Research (INDEHESA), University of Extremadura, Plasencia, Spain

L. Huntsinger
Department of Environmental Science, Policy, and Management (ESPM), University of California, Berkeley, USA

T. Plieninger
Department of Agricultural Economics and Rural Development, University of Göttingen, 37073 Göttingen, Germany

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Introduction

Mediterranean vegetation—a mosaic of shrublands, woodlands, pastures, and fields—is wildfire prone. Mild and wet winters promote biomass accumulation and are followed by hot summers that make the vegetation dry and flammable (Keeley et al. 2012; Moreira et al. 2020). Historically, intentional, low intensity burning was a common land management practice based on traditional know-how, and used to expand pasture and cropland (Rego et al. 2010). Clearing dense vegetation contributed to a diverse landscape and reduced fuel loads (Ortega et al. 2012; Damianidis et al. 2021). However, things have changed. Today, one of the major causes of wildfires is escaped fire from intentional burning (Rego et al. 2010). In recent years, hot and fast spreading fires, so called megafires, increasingly threaten whole social-ecological systems and have become a problem for Mediterranean regions globally (Lindenmayer and Taylor 2020; Safford et al. 2022). In the last decade an annual average of 450 000 ha have been burned in the Mediterranean Basin (FAO and Plan Bleu 2018). Large fires are defined as fires that affect more than 500 ha and cannot be controlled due to flame size, fire speed, or canopy fire (Alló and Loureiro 2020). Drivers include climate change, land-use change, land abandonment and short-sighted fire suppression policies (Moreira et al. 2011, 2020; Moreno et al. 2014; Gan et al. 2015; Varela et al. 2020).

Mediterranean rural landscapes are subject to land abandonment and rural depopulation (Azevedo et al. 2011). The resulting land use change challenges the biodiversity and ecosystem services supported by traditional agro-silvo-pastoral systems characteristic of these areas (Varela et al. 2020; Quintas-Soriano et al. 2022). Without grazing, burning, cultivation, or clearing to keep regrowth in check, abandoned lands and burned areas become dense shrublands and forests, increasing fuel loads, and creating continuous fuels fostering wildfire spread (Varela et al. 2020). Such lack of forest management results in larger, hotter, and faster spreading wildfires (Damianidis et al. 2021).

For decades, existing top-down wildfire mitigation policies have focused on fire suppression in Spain and other Mediterranean regions (Moreira et al. 2020). However, the result is a "fire paradox": when fires are suppressed, absent other vegetation control methods, vegetation grows freely, and biomass accumulations build fuel loads over time, eventually feeding megafires (Rego et al. 2010). Creating fire-resistant landscapes (DeRose and Long 2014) has therefore emerged as key to reducing large wildfires (Moreira et al. 2020). One option is creating a network of linear strips of bare soil (fire breaks) or low biomass vegetation (fuel breaks) (Ascoli et al. 2018). Fire and fuel breaks can slow down fire spread and can act as an anchor for fire suppression (Duguy et al. 2007; Oliveira et al. 2016). However it is necessary to transform a high percentage of the landscape (e.g. 20–30%) into fuel or fire breaks to effectively change fire incidence (Oliveira et al. 2016), calling for the integration of local community engagement into wildfire mitigation at the landscape scale. Payment schemes for implementing fire breaks and fuels reduction through shrub clearing and/or grazing have been successfully implemented, for example, in La Rioja and Andalusia (Lasanta et al. 2018; Varela et al. 2018).

Implementing and maintaining agroforestry systems can be an important pathway for mitigation wildfire risk by decreasing fuel loads, changing fuel characteristics, and acting as fuel breaks that cover extensive areas (Moreira et al. 2020; Damianidis et al. 2021). They can maintain aesthetically pleasing landscapes, provide products for human use, and support carbon sequestration in trees unlikely to be consumed by fire. Trees are fewer than in forests and spaced more widely, while management for grazing and/or cropping results in less continuous understory biomass and less woody vegetation than in unmanaged grasslands and shrublands (Varela et al. 2020; Damianidis et al. 2021). In the Spanish region of Extremadura, they may also restore and maintain traditional agro-silvo-pastoral landscapes such as *dehesa*. Dehesa landscapes have been found to be among the most fire-resistant in Spain but are in decline, while more fire-prone landscapes have increased (Ortega et al. 2012). Extensive agroforestry systems can act as "productive fuelbreaks" for communities surrounded by fire-prone vegetation (Bertomeu et al. 2022).

Essential components of successful wildfire mitigation are bottom-up strategies with region-wide stakeholder collaboration (Gan et al. 2015). Worldwide, such multi-stakeholder collaborations have been promoted under the umbrella of "integrated landscape initiatives." An integrated landscape initiative is a

group of people from different sectors with common goals, supporting a variety of landscape values. They actively engage in land management, awareness raising, and education (García-Martín et al. 2016; Carmenta et al. 2020). In many parts of Europe, *neo-rurals* (people that have moved in the last two decades from urban to rural areas for living and working on the land) play a role in integrated landscape management as they are growing in number and often seek new models of sustainable land management, the experience of living close to nature, and engagement in local, healthy food production (Escribano and Mormont 2007; Orria and Luise 2007).

Considered a holistic approach to landscape management (García-Martín et al. 2016), integrated landscape initiatives are increasingly supported by funding bodies at local to global scales (Sayer et al. 2017). In recent years, "landscape thinking" and the need to empower rural communities has been widely recognized in risk mitigation strategies, and in particular as a complement to top-down wildfire suppression approaches (Prior and Eriksen 2013; Carroll and Paveglio 2016). Collective engagement in wildfire mitigation in the Mediterranean Basin has been analysed by Górriz-Mifsud et al. (2019), with a focus on community-based fire preparedness and suppression. How to expand fuel treatment strategies to the landscape scale on Lesvos island, Greece, was studied by Palaiologou et al. (2020). Otero et al. (2018) did research on integrating local communities into decision making for wildfire suppression and preventive mitigation planning in Catalonia, Spain. However, little is currently known about participant motivations and perceptions of the outcomes of integrated landscape initiatives in wildfire mitigation. In particular, the role of stakeholder cooperation in land management in relation to the use of traditional practices and local knowledge has not yet been studied. Here, we contribute to the literature the perspectives of diverse land managers on wildfire mitigation. Our study aims to explore the social-ecological dimensions of the integrated landscape initiative in Extremadura, Spain, known as "MOSAICO" (further referred to as "the initiative"). The Initiative seeks to reduce the impact of wildfires through management of fire-resistant multifunctional mosaic landscapes and use of productive fuel breaks that are often adaptations of traditional agricultural systems, most notably silvo-pastoral agroforestry. Drawing on a survey of participating land managers, we address the following questions: (1) What motivates land manager participation?, (2) How do participants perceive the outcomes of the integrated landscape initiative? And, (3) Are there differences in responses about motivations, barriers, outcomes, and wildfire-related measures between rural and neo-rural land managers? We present our results and discuss the integrated landscape initiative as a model for collaborative wildfire mitigation, highlighting agroforestry as a tool for promoting fire-resistant landscapes, and closing with policy recommendations.

Methods

We chose an in-depth case study approach aiming for holistic insights in a complex field (Brown 2008). The approach allows in-depth, multi-faceted explorations of complex issues in their real-life settings. It provides the opportunity to explore the key characteristics, meanings, and implications of the topic, identifying areas for further research (Crowe et al. 2011).

Study area and local context

The case study area is in a rural part of western Spain, the adjacent counties of Sierra de Gata and Las Hurdes in northern Cáceres Province of the Extremadura Autonomous Region (Fig. 1). Sierra de Gata is 1257.94 km^2 in size with 19 municipalities. The initiative is active in several of these municipalities such as the municipality of Valverde del Fresno with 2250 inhabitants and Gata with 1413 inhabitants. Las Hurdes is 499.37 km^2 in size and consists of 6 municipalities, including the largest two, Caminomorisco with 1181 inhabitants, and Pinofranqueado with 1692 inhabitants (IEEX 2021). The climate in the area is typically Mediterranean, with mild, wet winters and hot, dry summers.

Sierra de Gata and Las Hurdes are far away from major transportation routes. Isolation has contributed to local development of a rich cultural heritage and ecological knowledge linked to traditional landscape management (Catani 2004; Solymosi 2011). The landscape was largely a mosaic of agroforestry uses, dominated by pasture with tree crops (Montiel-Molina et al. 2019). Dry stone terraces used for fruit

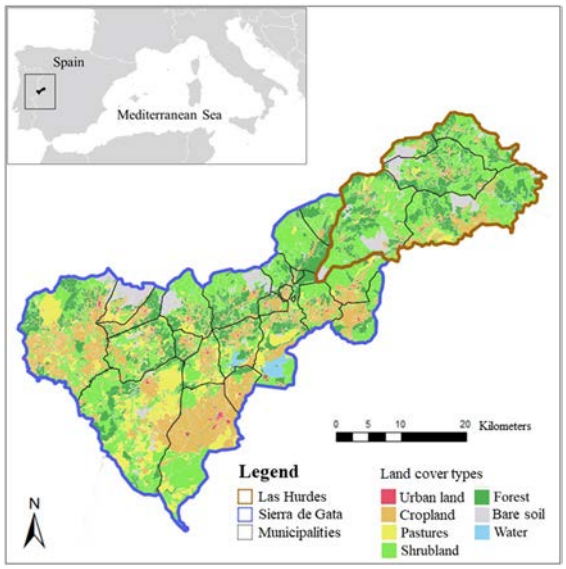

Fig. 1 Maps of the study site, the counties of Gata and Las Hurdes in Extremadura, Spain (REDIAM 2007)

and vegetable cultivation have been common (Abel-Schaad et al. 2014). The afforestation policy of the Franco regime (1940–1975) resulted in massive pine plantations which are positively correlated with forest fire occurrence (Iriarte-Goñi and Ayuda 2018). Since the 1950s, industrialisation and socio-economic crises have fueled outmigration, leaving a population of rising average age (Madruga et al. 2021). This rural depopulation also caused land abandonment, abandonment of livestock grazing and resulting in forest encroachment, and in consequence flammable biomass accumulation and a more fires (Iriarte-Goñi and Ayuda 2018). The traditional agroforestry that once blanketed the rough topography of our study region has substantially decreased in area, first in Las Hurdes (since the 1930s) and later in Sierra de Gata (since the 1960s). Nowadays, national and regional regulations hamper land use change from forest to agricultural land, and grazing is rarely allowed in public forests. An abandoned agroforestry system crowded with trees is typically reclassified as forest, limiting its use for livestock husbandry and cultivation. If a forest burns down, the land can be converted to farmland only after 30 years. Forest ownership is related to forest condition, with public forests receiving the highest investment in silvicultural treatments and fire suppression infrastructure. Private forests are short of active management due to low or no profitability, except in those areas managed under public–private agreements. In Sierra the Gata and Las Hurdes, 2.298 wildfires burned on 37.500 ha between 2000 and 2015 (Bertomeu et al. 2019). Despite a decline in fire occurrence and burned area between 1983 and 2021, a greater fraction of area was burned in large (>500 ha) or very large (>5000 ha) fires (Ministerio de Transición Ecológica 2022). In 2015, a single megafire in Sierra de Gata burned nearly 8000 ha (Bertomeu et al. 2022). In the region, most resources are allocated to fire suppression infrastructure (most commonly firebreaks and firefighting equipment). Prevention is generally small-scale fuel removal treatments around cities and preventive silvicultural treatments in pine stands.

The MOSAICO initiative

The major aim of the MOSAICO initiative in Sierra de Gata and Las Hurdes is to foster mutual learning among local stakeholders and collaboratively engage in wildfire mitigation using "productive fuel breaks," areas maintained by agroforestry practices (Varela et al. 2020). The initiative is supported by the University of Extremadura, the Government of Extremadura, and the European Union. Land managers apply to for initiative membership, and are accepted if they contribute to fuel reduction through forest management, livestock grazing, crop cultivation, or agroforestry. Examples of such activities include establishment of goat herding, planting of fruit trees, resin harvesting, pine tree biomass harvesting, and implementation of new practices like rotational grazing. The average size of properties managed as part of the initiative is 63.8 ha. The initiative provides administrative, field technical advice, and other services, including support in completing and submitting funding applications.

Survey design

Our questionnaire sought insight into land manager perceptions of the integrated landscape initiative and consisted of 7 thematic sections about: (1) land managers characteristics, (2) land managers activities (3) aims/motivation, (4) perceived outcomes/performance of the initiative, (5) perceived barriers

to management success, (6) perceived success factors for initiative goals, and (7) perceptions of wildfires (Supplementary Material 1). We developed questions and statements covering these themes after intense discussions with experts in the region. Most answer options were in a likert scale format, i.e. for each the respondents had to indicate their level of agreement on a scale from 1 to 5 (e.g. 1 = strongly disagree to 5 = strongly agree, with 3 indicating neither agree or disagree) (Joshi et al. 2015). In some cases, respondents could complement predefined answers with their own options (e.g. motivations). To help explain and supplement answers to predefined questions, and to allow respondents to add issues they felt were missing in the predefined questions, we added open-ended questions (e.g. on outcomes of the initiative).

Data collection and analysis

We surveyed land managers that were part of the integrated landscape initiative MOSAICO (Varela et al. 2020; Bertomeu et al. 2022). Some landowners may not live on or manage the land. We are interested in the land managers perceptions, who are actively involved in full or part time land management and often live on the land. Contact information for 141 land managers was provided by the initiative. We aimed to include all land managers that considered themselves active members. Applying this criterion reduced eligible respondents to 95. Out of these 95, 10 declined participation and 19 were not available via phone and/or did not respond to our emails. In the end we conducted 66 interviews, corresponding to a rather high response rate of 69% (García-Martín et al. 2016; Carmenta et al. 2020). Wherever possible, face-to-face interviews were conducted by field assistants from September to December 2020. Enumerators followed safety protocols for COVID-19 risk. Informed consent was obtained.

Nine respondents prefered telephone, two e-mail interviews. Field assistants recorded participant answers for digitizing and translating into English. Of the 66 respondents, three responses had to be removed from the analysis because interviews revealed that they were not actively engaged in land management, so a total of 63 surveys were used for the analysis.

Due to the exploratory character of our study (and as variance of responses was low across all categories), we most often used frequency analysis. We calculated response mean values and ranked them according to levels of agreement. For the comparison of rural versus neo-rural participants, we conducted nonparametric statistical comparison analysis (Mann Whitney test) including 62 surveys, as one respondent could not be identified as rural or neo-rural. Answers to open-ended questions were used to support, supplement or challenge the findings of the quantitative analysis.

Results

Land managers and farming activities

The majority of land managers were 36 to 50 years old (57%). 14% were younger, 24% were 51 to 65 and a very few (5%) were 65 + years old. Of the interviewed land managers 27% were female. With 42%, nearly half were neo-rurals. Participation in the initiative lasted from 1 to 5 years and a similar number of people joined the initiative each year leading to our cumulative total participants. The majority of respondents practiced land management as a side job–62% earned 25% or less of household income from farming activities. Only 19% of farming activities contributed 76–100% to household income, while 11% of land managers earned 51–75% and 8% of land managers earned 26–50% of household income from land management. Farms were mostly managed by single persons (38%) or families (44%), only 10% of the farms had 2–5 workers and 8% had more than 5 workers.

Land managers had between one and ten different activities on their farm (Tab. 1). Farms were often agroforestry systems, e.g. sheep husbandry in a chestnut orchard (Fig. 2). The most common land management activities were olive and chestnut orchards, livestock husbandry, and agroforestry. Other fruit trees grown included cherries, almonds, pistachios and figs. Around 15% of land managers produced fuelwood, resin, timber, dairy and/or aromatic plants. Production of honey, vegetables, herbs, poultry, cereals, cork and snails as farming activities was rare. In an open-ended question, we asked the respondents how they defined themselves as a land manager. We got diverse answers such as: “a farmer for hobby and entertainment; as

Table 1 Respondent's most common activities on their farms

Within-farm activities	Portion of all farms [%]	Within-farm activities	Portion of all farms [%]
Livestock husbandry	40	Wood fuel	16
Olive trees	35	Resin tapping	14
Agroforestry	32	Forestry for wood	14
Chestnut trees	32	Dairy farming	14
Other fruit trees	27	Aromatic plants	14

Fig. 2 Common agroforestry practices in the integrated landscape initiative: Sheep and sweet chestnuts (top left), cows with kiwi (top right), goat herding in a semi-open landscape (bottom left), unburned grazed fruit orchard surrounded by burned forests (bottom right). Note the discontinuous tree canopies and the sparce understory fuels in the agroforestry systems

a motivated beginner; as a caretaker, responsible for the environment; as a happy farmer; as a rural farmer and rancher; as an example for people to follow; as a fighter for agroforestry."

Wildfires: Impacts and approaches

Respondents were asked about wildfire impacts and suitable measures for combating them. More than half fully or mainly agreed they were strongly affected by wildfire (Fig. 3a), with the vast majority in full agreement. Only a fifth fully disagreed that

they were strongly affected. Half mainly or fully agreed that wildfires caused psychological distress for a member of their farm. Nearly 40% of the farms were physically damaged by wildfire. About half of the land managers fully or mainly agreed that combating wildfire was their main reason for joining the initiative.

We listed potential measures against wildfires and asked about their usefulness (Fig. 3b). All land managers indicated that three were either very helpful or helpful: "promoting agroforestry," "promoting cultivation" and "promoting grazing." Almost all managers agreed with "promoting forestry." There was some disagreement with "strengthening prevention," "more regulations," and "increasing resources for conventional measures," such as increasing number of fire-fighting helicopters, though more than half still agreed these were helpful or very helpful.

Motivations

We asked about the importance of various motivations for their land management as part of the initiative (Fig. 3c). Over 80% agreed that most of the items listed strongly or very strongly motivated them to engage in land management and the initiative. The most motivating was "combating depopulation" followed by "preserving landscape beauty" and "improving personal well-being," with no respondents ranking them as weak or very weak motivations. These were followed by "preserving cultural heritage," "improving local livelihoods," and "combating wildfires."

Barriers to success

We asked land managers to agree or disagree with statements about the severity of possible barriers to success for their activities (Fig. 3d). Interestingly, lack of legislation adapted to the current fire situation and of political support were perceived as having a greater negative impact than a lack of funding and profitability. More than half of the land managers found a "lack of adapted legislation" to be a high or very high barrier. The barrier with the second highest impact was a "lack of political support," followed by a "lack of funding" and a "lack of profitability." Lack of experts was considered the lowest barrier.

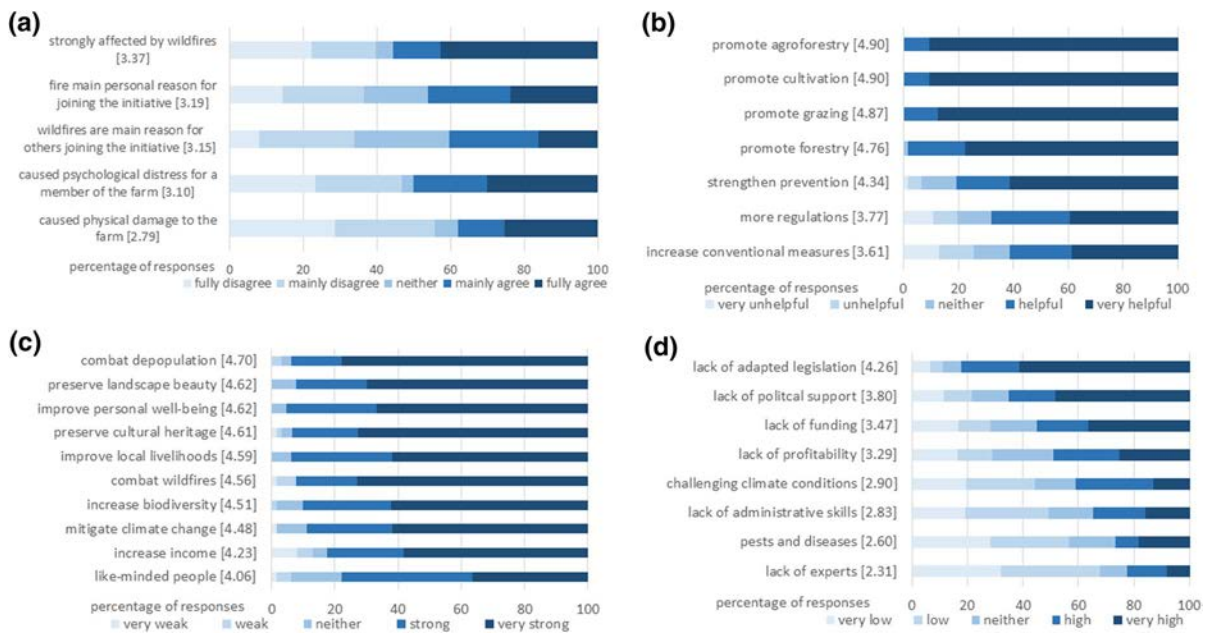

Fig. 3 Farmer perceptions of **a** Wildfire impacts, **b** Measures against wildfires, **c** Motivations for land management and **d** Barriers to success. Color intensity reflect answer categories. Mean values are shown in brackets. (Color figure online)

Outcomes

We enquired about perceived regional and personal outcomes of the initiative. Regarding regional outcomes, "helped combating wildfires" was agreed with by the most respondents (Fig. 4a). "Increased local ecological knowledge" was second, very closely followed by "increased biodiversity" and "increased sustainable land management." Over 80% agreed or strongly agreed with four statements above, and only 2% strongly disagreed. "Counteracted abandonment," "improved the regional economy," and "improved the well-being of locals" were agreed with by more than half of the land managers, while only 2 to 4% strongly disagreed with them.

The rate of agreement about personal outcomes was more differentiated (Fig. 4b). The strongest agreement, by more than half, was that they had "more enthusiasm about traditional land management." There was a similar distribution of agreement with "fullfilled personal expectations." As we found out from an open-ended question, this fulfillment mostly referred to advice and consultation for land management and coping with bureaucracy (about 30% of participants). About 13% of respondents stated in the open-ended question that collaboration, combating wildfires, or an increase in yield/profitability from joining the initiative were expections fulfilled. There were also a few that mentioned that fighting abandonment fulfilled personal expectations.

The third personal outcome most respondents agreed with, and with the highest percentage strongly agreeing, was that the initiative "helped to overcome administrative barriers." This was followed by "increased management skills," "increased collaboration among land managers," "improved personal wellbeing," "increased crop diversity," "increased profitability," and "led to closer contact with consumers." The last, "increased customers," still had a fourth of respondents agreeing with it, though few strongly agreed.

To complement the statements about outcomes, we asked the land managers in an open question about what had changed on their farm since they joined the initiative. About half of stated that there were no changes. Some further explained that they are still in the initial stages of the common project so it was too early to say. The most frequent change was gaining

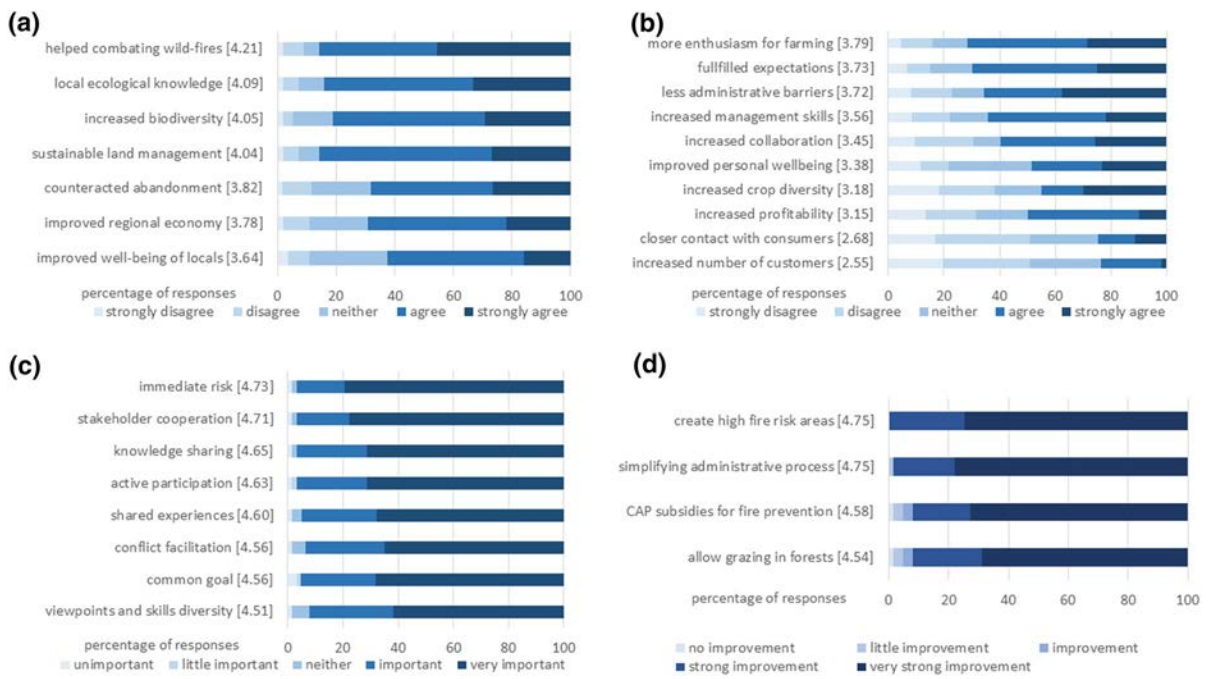

Fig. 4 Farmer perceptions of **a** Regional outcomes, **b** Personal outcomes, **c** Success factors and **d** Policy recommendations. Color intensity reflects answer categories. Mean values are shown in brackets. (Color figure online)

knowledge and advice. Changing crops, cultivation of abandoned land, and changing grazing methods to rotational grazing to avoid overgrazing were mentioned 4 times. More focus on fruit trees was mentioned 3 times, especially chestnuts (mentioned twice). Other outcomes mentioned were changing farming techniques, starting to label products, and no longer feeling alone. One stated that he now sees "the natural environment from another perspective."

Success factors

We asked respondents to agree or disagree with the importance of possible success factors for the initiative. The majority (over 60%) of land managers perceived all the suggested success factors as very important (Fig. 4c). The most important was "fighting a common and immediate risk like fire." Second was "cooperation between different stakeholders and sectors." This was followed by "knowledge sharing," "active participation," "shared experiences," "conflict facilitation," "having a common goal," and having "a diversity of viewpoints and skills."

Policy support

We asked respondents to assess policy options in terms how important each would be for improving wildfire mitigation. All options received strong support from land managers (Fig. 4d). All agreed that creating a special land management regime would be an improvement. Simplifying the administrative process was considered a very important possible improvement by most, for another fifth it was a strong improvement and very few agreed with little improvement. This high agreement also shows that MOSAICO administrative advice is important to participants, including help for establishing an enterprise, applying for CAP subsidies, and requesting permission for special land management (like cutting or planting trees). "Make changes in the Common Agricultural Policy (CAP) to subsidize the fire mitigation service provided by land managers" was regarded as a very strong or strong potential improvement by almost all. The lowest ranked of the four policy support options, "Allow grazing in forests" was still perceived as potentially a very strong improvement by more than two-thirds of the land managers and as "a strong improvement" by another fourth.

Differences across rurals versus neo-rurals

Neo-rural and rural land managers differed in some of their responses, especially for motivations and wildfire measures (see Suplementary Material 2). Neo-rural respondents showed higher motivations compared to rurals on: increasing biodiversity ($U=387.5$; $p=0.012$), growing their own food ($U=273.5$; $p=0.003$) and improving personal well-being ($U=323.5$; $p=0.010$), while rurals were more motivated by mitigating climate change compared to neo-rurals ($U=409.5$; $p=0.019$). Neo-rurals perceived pest and diseases as a higher barrier than rurals ($U=320.0$; $p=0.029$). We did not find statistical differences among further perceived barriers and outcomes. Regarding measures to mitigate wildfires, rurals rather than neo-rurals more often perceived the promotion of grazing ($U=488.0$; $p<0.0001$) and cultivation ($U=483.0$; $p<0.0001$) as helpful, while neo-rurals were more favorably inclined toward agroforestry ($U=452.0$; $p<0.0001$) as a helpful measure, although both groups mainly agreed to the helpfullness of all three measures.

Discussion

Large-scale catastropic wildfires are on the rise in the Mediterranean region, and there is increasing awareness that preventing and reducing their impacts most often requires cooperation among land managers at the landscape level. To understand the complexities of such cooperation, we performed a first exploratory survey of a community-based initiative for wildfire mitigation in Europe, providing insights into land manager perceptions of their motivations for participation, and of initiative barriers to success and outcomes for the individual as well as for the local population. Land managers found collaborative wildfire management was multifunctional, reducing fire hazard, reviving abandoned landscapes, and increasing biodiversity. Here we discuss how the investigated initiative offers a model for collaborative action with multiple benefits, highlighting the role of agroforestry, and then close with policy recommendations and conclusions.

A model for collaborative wildfire mitigation

The highest level of agreement about regional outcomes was that integrated landscape management "helped in combating wildfires," meeting the initiatives' main objective and making it a success for its members. We want to stress that our study is based on the perceptions of respondents, and these can be influenced by contextual factors notably including participation in social networks. The realised impact of the initiative regarding fire risk and potential spread is analysed in Bertomeu et al. (2022).

Reduction of fire risk was a main driver for collaborative action, and previous research has found that reducing fire risk is a common motivation for California landowner cooperation as reported by landowners (Ferranto et al. 2013). Our respondents agreed that wildfire impacts were broad and multifaceted, including causing psychological distress that touched land managers in half of the studied farms. This is an impact that has been somewhat neglected in the literature (Finlay et al. 2012; Waks et al. 2019).

Typically, integrated landscape initiatives develop to attempt to resolve land use conflicts, for example such as the spread of extractive industries into cultural landscapes, or when biodiversity conservation creates tradeoffs with livelihoods (Sayer et al. 2015). In contrast, our studied initiative seeks to collaboratively reduce wildfire risk by reviving management of abandoned land (Bertomeu et al. 2022). This is a new and globally important domain where integrated landscape initiatives can take meaningful action. Social cohesion is a key factor in creating a wildfire resistant and resilient community because wildfire risk reduction cannot be tackled effectively by individuals (Prior and Eriksen 2013; Townshend et al. 2015). Prior and Eriksen (2013) found in particular that community characteristics like "sense of community" and "collective problem solving" support adoption of fire preparation practices and the development of cognitive capacities that reduce vulnerability and support collaborative action. We found increased collaboration to be an outcome highlighted by respondents, an indicator of social cohesion. The shared immediate risk of wildfires, and the experience of developing and carrying out initiatives to reduce wildfire, pushed land managers to develop common purpose and shared goals. In our case, integrated landscape management promoted social cohesion via a framework for community wildfire mitigation. Similarly, Prior and Eriksen (2013) point out that community efforts should be acknowledged for their role in shaping the beliefs and attitudes of the participants. Effective development of shared goals and practices calls for engagement of people in risk communication and mitigation activities, rather than passive transfers of information (Tedim et al. 2016). Taking action ultimately relies on individual beliefs about what is meaningful, important and possible. Focus on individual and community empowerment can prevent being overwhelmed by a global-scale problem (Prior and Eriksen 2013). Local to regional efforts in collaborative action to solve environmental problems are at a level that empowers local people to actively engage and gives a feeling of self-efficacy (Górriz-Mifsud et al. 2019).

Agroforestry for fire resistant landscapes

In addition to reducing fire risk, establishing agroforestry systems has a critical role in sustainable and regenerative land management globally (Plieninger et al. 2020; Damianidis et al. 2021). Perceived increases in biodiversity and human wellbeing have often been achieved through the expansion of agroforestry systems (Damianidis et al. 2021). For instance, in an abandoned landscape, agroforestry practices help enhance diversity by restoring openings in the canopy and increasing habitat diversity (Varela et al. 2020). They also enhance carbon sequestration by retaining trees (Kay et al. 2019) and reducing the likelihood of fire risk (Damianidis et al. 2021).

Moreira et al. (2011) identified three strategies for fire resistant landscapes: creating and maintaining productive landscape-scale fuel breaks, reducing fuel loads, and substituting fire-prone species with more fire-resistant ones. Agroforestry systems, such the multitude of fruit orchards that form part of MOSAICO, encompass all these strategies: they reduce fire risk by establishing and maintaining productive fuel breaks, shrublands or pine forests are replaced with less fire prone vegetation and vegetation structure (e.g. chestnut orchards with sheep), and grazing reduces understory fuels and suppresses woody vegetation. Before land use abandonment, Sierra de Gata and Las Hurdes were models for fire resistant tree crop systems managed with grazing and forest clearing (Montiel-Molina et al. 2019).

When fire damage to agricultural and forestry goods is accounted for, Spanish silvopastoral agroforestry systems are more profitable than timber production alone (Moreno et al. 2014). Restoring burnt areas between 2013 and 2017 in Spain cost almost 70 million Euros. Spain is the country with the highest vulnerability to land degradation among European countries (Varela et al. 2020). To tackle these problems, the Catalonian Government has released a "Forest Policy General Plan" that suggests different management tools for decreasing fire risk. Casals et al. (2009) emphazise the importance of agroforestry to the Catalonian government's fire prevention plan. Animal grazing not only reduces wildfire risk and conserves biodiversity, but it is relatively inexpensive, offering a viable alternative to increasingly costly yet failing conventional supression measures (Bertomeu et al. 2022). Especially in combination with shrub clearing, livestock grazing is a effective tool in wildfire risk reduction (Lasanta et al. 2018). Animal grazing can also complement prescribed burning, reducing the hazard of escape with lower fuel loads (Rigolot et al. 2009; Davies et al. 2016).

Our respondents' perceptions were confirmed by a review on land cover and wildfire relations that identified grasslands and farmland as options for decreasing wildfire vulnerability (Moreira et al. 2011). Data from the northern Mediterranean reveals that agroforestry systems are less affected by wildfire, compared to forests, shrublands, or grasslands, and are also environmentally friendly and contribute to human well-being (Carmo et al. 2011; Damianidis et al. 2021). Strong agreement that forest harvest and management were very helpful for wildfire mitigation concurs with the high fire risk found in abandoned forests (Azevedo et al. 2011; Badia et al. 2019; Montiel-Molina et al. 2019).

Revival of rural cultural landscapes

Sierra de Gata and Las Hurdes are cultural landscape hotspots for their unique but threatened terraced landscapes. From 1960 to 1975, Extremadura lost about one third of its inhabitants due to emigration to cities–in some counties half of the people left, leaving an aging society behind (Rosado 2018). Outmigration results in abandoned land (Badia et al. 2019), food security decline, decreased biodiversity, loss of multiple services from multifunctional land use, and a breakdown in social structure and cultural practices (Perpiña Castillo et al. 2020). Combating rural depopulation was the highest ranked motivation for initiative participation, with cultural heritage and increasing landscape beauty also among the most important motivations for land managers. Similar results have been found for integrated landscape initiatives in Europe (García-Martín et al. 2016).

Profitability is a major driver for stewardship of agroforestry landscapes and its lack is one of the main drivers of abandonment (Wolpert et al. 2020). "Increased income" through land management was important for many respondents. Most are only part time land managers—presumably small scale farming does not provide enough money to support livelihoods, and better incomes are sought in urban areas. Reversing this trend is needed to regain thriving, multifunctional agroforestry landscapes that offer livelihoods and well-being for people while preserving cultural landscapes (Howkins 2003). Some of the land managers in our study noted that their recently planted and carefully husbanded fruit trees were not even yielding yet, which shows commitment to the future. Eight percent of respondents reported "increase income" as a very weak motivation, finding it "very weak motivation" more often than any other motivation option. This may reflect the findings of Oviedo et al. (2017) that farmers are (if they can afford) often motivated as much if not more by amenities like living in nature and having a desirable lifestyle than by profits.

The movement of neo-ruralism is is getting more and more attention since it is a widespread trend in Europe (Bender and Kanitscheider 2012; Dal Bello et al. 2021). Neo-rurals are characterised as farmers that moved to rural areas as a response to the Green revolution and critique of city life (Escribano and Mormont 2007), seeking to protect biodiversity and grow high quality local food (Orria and Luise 2007). Previous research has also highlighted how rural environments are attracting neo-rurals as new entrepreneurs for various reasons, especially in search of a better quality of life (Dal Bello et al. 2021; Dall Bello et al. 2022). This is in line with our findings that showed that "increasing biodiversity", "growing their own food" and "improving personal wellbeing" as more important motivations for neo-rurals compared to rurals in managing their land. Rurals were more motivated than neo-rurals by "mitigating climate

change" which could be due to their own experience with changing climatic conditions, including drought. The high motivation to mitigate climate change in both groups is surprising as farmers seem to have a very low awareness of climate change globally (Madhuri 2020; Saliman and Petersen-Rockney 2022). In the current context of rural land abandonment, the incorporation of neo-rural populations may provide new opportunitites both for revitalising rural economies (Renau 2018; Dal Bello et al. 2022), and for the conservation of cultural landscapes (Pérez and Gurría 2010). As our results indicate, neo-rurals may show stronger motivations linked with pro-environmental behaviour. They might bring in innovative practices and think more globally. This could fruitfully complement the local traditional knowledge and experience of rural people. Collaboration among these groups could provide hope for the revival of cultural landscapes.

Policy recommendations

Land managers perceived the lack of political support, and legislation not adapted to current fire conditions, as very strong barriers, even greater than a lack of funding. In other European initiatives, lack of funding was by far the biggest barrier identified (García-Martín et al. 2016). The reason may be uncontrolled forest expansion fostered by national and regional regulations that do not allow grazing in former forest areas, as described previously. García-Martín et al. (2016) found that among different professional groups, land managers in particular often have to cope with narrow and inflexible policies ill-matched to local conditions.

All land managers agreed with policy to "create a special land management regime for areas with high fire risk." This would help land managers to better assess wildfire risk in their area and identify areas where management is needed. It could also provide a basis for territorial planning processes (Marey-Perez et al. 2021). "Decreasing bureaucratic requirements" was strongly supported by respondents. This can be an important step in making active land management more attractive and providing straightforward funding opportunities. Over 90% of land managers agreed that CAP subsidies for fire mitigation services, like grazing, would improve the situation and that a legal basis to allow grazing in forests is needed. Managing forests to decrease biomass reduces wildfire risk and increases efficiency of water use (Varela et al. 2020).

Conclusion

The increase of megafires in the Mediterranean region requires new approaches for wildfire mitigation. The use of community-based agroforestry as a complement to top-down firefighting strategies is increasingly discussed. In our study of an integrated landscape initiative we found highy motivated land managers that perceived manifold beneficial personal and regional outcomes from such action. Our study offers the following key lessons:

- Integrated landscape initiatives not only help resolve land use conflicts, but may be extended to also support collaborative efforts to mitigate wildfires.
- Different land managers (livestock farmers, foresters, tree crop farmers, arable farmers) show high levels of agreement in their motivations for participating in integrated landscape management and in their perceptions of positive personal and regional outcomes from such an initiative.
- Wildfire mitigation through community-based agroforestry can also serve as leverage point for financing rural revival and provision of multiple ecosystem services.
- Neo-rurals and rurals differ in some of their perceptions and motivations. These might complement each other in efforts to revive landscapes that are being abandoned.
- Policy should support land management that reduces wildfire risk by adapting legislation and funding schemes.

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Authors contribution All authors contributed to the study conception and design. Material preparation and analysis were performed by FW. Data were collected by local field assistants and interviews translated by CQ-S. The first draft of the manuscript was written by FW and all authors commented on and

revised the manuscript. All authors read and approved the final manuscript.

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Data availability Anonymized raw data are archived on the Zenodo repository, https://doi.org/10.5281/zenodo.7157514

Declarations

Conflicts of interest We assure that we do not have a conflict of interest. Fernando Pulido is a member of the MOSAICO project team. He was not involved in the performance of the interviews.

Ethical approval According to the rules of University of Kassel, no formal ethics review is needed for this type of survey.

Consent to participate Participants agreed in participation.

Consent for publication Participants agreed in publication of anonymised data.

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Article III

Integrating perennial staple food crops in agroforestry systems: A case study of chestnut (Castanea sp.) in Germany

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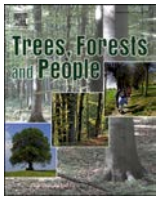

Integrating perennial staple food crops in agroforestry systems: A case study of chestnut (Castanea sp.) in Germany☆

Franziska Gaede (b. Wolpert) [a,e,*], Cristina Quintas-Soriano [b], Bill Davison [c], Tobias Plieninger [a,d]

[a] Faculty of Organic Agricultural Sciences, University of Kassel, Steinstraße 19, 37213 Witzenhausen, Germany
[b] Biology and Geology Department, Andalusian Center for the Assessment and Monitoring of Global Change (CAESCG), University of Almeria, Almería, Spain
[c] Savanna Institute, 2453 Atwood Avenue, Suite 209, Madison, WI 53704, United States
[d] Department of Agricultural Economics and Rural Development, University of Göttingen, Platz der Göttinger Sieben 5, 37073 Göttingen, Germany
[e] Present address: Faculty of Forest Sciences and Forest Ecology, University of Göttingen, Büsgenweg 2, 37077 Göttingen, Germany

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ABSTRACT

In a time of multiple global challenges, trees gain more and more attention as an important component of sustainable land use systems, as they can produce food and provide multiple other ecosystem services at the same time. In Germany, traditional orchard meadows (so-called "Streuobstwiesen") are in decline, although they are well known for their ecological value. In modern agroforestry systems staple perennial food crops seem to be rarely integrated. Here, we propose to use emerging chestnut cultivation for revitalizing traditional orchard meadows, diversifying forests, and integrating perennial staple food crops in modern agroforestry systems. In this study, we interviewed 64 chestnut growers in Germany and aimed to (1) explore characteristics of chestnut stands and management; (2) evaluate the main motivations, aims, and challenges of chestnut growers; (3) identify perceived outcomes of chestnut cultivation and measures for upscaling; and (4) analyze differences between groups of chestnut growers. Our results show that most growers aimed to increase tree numbers and foster the spread of chestnut trees as cultural assets. Sustainable food production was the motivation most often named by the respondents. A guide for cultivation, as well as better funding, were mentioned as the most wanted and easy to implement measures for up-scaling production and consumption. Junior chestnut growers were better connected to other chestnut growers and were more motivated by sustainable food production than senior growers. Pest and diseases as well as legal and funding situations were aspects hampering chestnut cultivation. We suggest that chestnut trees can serve as a valuable element of a diverse tree crop landscape providing staple food crops while supporting ecosystem services.

Introduction

Worldwide, there is an ongoing polarization of land use and, subsequently, a disconnection of food production from the provision of other ecosystem services. On the one hand, there is land-use intensification including an increase in industrial inputs such as fertilizer, pesticides, and fuel for food production (Valenzuela 2016), and on the other hand, many food production landscapes are abandoned (Rey Benayas et al., 2007). Intensification and abandonment of food production landscapes can lead to loss of biodiversity (Uchida and Ushimaru 2014). Biodiversity is not only the basis of many ecosystem services, but also provides resilience in an uncertain future regarding climate change and the global spread of pests and diseases (Altieri and Paul Rogé, 2010; Sgrò et al., 2011). The negative impacts of the current global food system on ecosystem health are well known (Ickowitz et al., 2022). Agricultural production has been a major driver of biodiversity loss since pre-industrial times (Benton et al., 2021). According to the publication "Food in the Anthropocene", of the EAT-Lancet Commission, a great food transformation is, therefore, necessary (Willett et al., 2019).

Trees and shrubs are well known to provide multiple ecosystem services. The combination of woody perennials with cropland and/or pasture in the same land-use system to acquire beneficial interactions

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* Corresponding author.
E-mail address: franziska.gaede@uni-goettingen.de (F. Gaede (b. Wolpert)).

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between components, is known as agroforestry (Smith et al., 2012). Examples of ecosystem services provided by trees include soil erosion control, carbon sequestration, enhancing soil fertility, and cultural ecosystem services such as recreational, aesthetic, and cultural heritage values (Torralba et al., 2016; Toensmeier, 2016). Tree planting is one of the main solutions for climate change mitigation (IPCC, 2019). If those trees bear food crops, they can play an essential role in solving global food system challenges and enabling long-term sustainability, whilst tree crop landscapes are known as biodiversity hotspots, like "dehesas" in Spain (Kreitzman et al., 2020; Ickowitz et al., 2022). Nearly a century ago, the substitution of tilled agriculture by perennial tree crops as well as genetic improvement through breeding was suggested by Smith (1929). Still nowadays, perennials, including tree nuts, are an overlooked, but valuable source of staple foods that provide carbohydrates, fats, and/or proteins (Kreitzman et al., 2020; Davison et al., 2021). Perennial staple food crops are underestimated in their potential as a part of modern agroforestry systems as well as in current debates on agricultural transformation as they provide food and foster ecosystem service supply, however they are for example rarely integrated into modern agroforestry systems (Ferguson and Lovell, 2014; Kreitzman et al., 2020).

Throughout history, tree nut landscapes have been integral parts of staple food provision and the culture of societies worldwide. Famous examples are the walnut (*Juglans regia*) and pistachio (*Pistacia vera*) forests of Kyrgyzstan (Kreitzman et al., 2020), hazel (*Corylus avellana*) culture in Central Europe (Holst, 2010) and Balanoculture (*Quercus* sp.) in several regions of the world, including the Middle East (Bainbridge, 1985). In the Mediterranean Basin, sweet chestnut (*Castanea sativa*) served as the staple food crop for many civilizations. Due to its high carbohydrate content, it was referred to as the bread tree. In Corsica, it was an integral part of the culture and represented a symbol of freedom and independence (Wolpert et al., 2020). In Germany, orchard meadows with a combination of different standard-sized and habitat-rich fruit and nut trees are iconic, including apple, pears, cherries, plums and walnuts. They are called "Streuobstwiesen" (Forejt and Syrbe, 2019).

In the course of land-use intensification, open woodlands, such as orchard meadows have decreased in Germany and worldwide (Bazzato et al., 2022; Hammel and Arnold, 2012; Hanberry and Abrams, 2018). "Streuobstwiesen" were largely substituted by dwarf tree plantations for fruit production. The transition was financially supported by the federal and state government of Germany from 1957 to 1974. The number of orchard meadow trees was estimated to have decreased by approximately half of its former quantity from 1965 to 2005 in South-Western Germany (Hammel and Arnold, 2012). Nowadays, the societal and ecological values of trees are well-known and different programs from federal states or public organizations aim to sustain and promote these valuable cultural tree landscapes. However, those programs have not succeeded in reversing the orchard meadow decline trend (Hammel and Arnold, 2012; Plieninger et al., 2015). Often, a lack of profitability leads to the abandonment of orchard meadows (Plieninger et al., 2015). The integration of less work-intensive and more profitable new crops with higher market value may be one way to safeguard the maintenance of orchard meadows.

It seems that chestnut trees, as fruit trees, are not common in Germany, but have been increasingly planted in forests, croplands and orchard meadows in Germany in the last few years. There is high potential for chestnuts to become a part of modern agroforestry systems in many parts of the world (Kreitzman et al., 2020). As a carbohydrate source, chestnuts may play an important role in substituting annual crops to enable the concurrent provision of staple food crops and multiple other ecosystem services (Segatz, 2018; Davison et al., 2021). In contrast to traditionally used fruit trees such as apples and pears, chestnut trees do not require much work, which allows to maintain them at a landscape scale (ripe fruit fall to the ground and less pruning is needed), harbor high biodiversity (Segatz, 2018), and can be potentially profitable (Davison et al., 2021).

Chestnut trees are highly multifunctional in their uses and benefits: Traditionally, the main management options have been either groves for fruit production (including grazing animals and high forests for timber and fruit production) or coppice for poles production and firewood (Lüdders, 2004; Conedera et al., 2016). Due to the high tannin content, the wood is very durable and is therefore used for fence poles, and also for wine barrels. In the second half of the 18th century, chestnut coppices were widely spread with grape production in Germany, as wood was used as lattice posts (Konold and Jotz, 2012). In addition to wood utilization, chestnut litter has been traditionally exploited for fertilizing vineyards (Lang, 1971). In the late Middle Ages (ca. 1250–1500), chestnut fruits were increasingly seen as valuable goods for trade, were shipped to England and the Netherlands (Bouffier and Maurer, 2009), and served as a staple food crop (Lang, 1971). Chestnut fruits have a nutrient profile similar to annual food crops such as brown rice and corn (Davison et al., 2021). The fruits can be roasted, cooked, dried, milled, cracked, baked, or candied. They are valued not only for human consumption but also for feeding animals like pigs (Lang, 1971).

In this study, we selected chestnut trees as a case for a tree crop that provides staple food. Chestnuts could be an important element in modern food production systems as perennial carbohydrate sources (Davison et al., 2021), and can also play a role in revitalizing traditional orchard meadows as a low-maintenance, potentially profitable crop and to accelerate returns from forests through fruit and nut production. Chestnut fruit production in Germany is currently rare, and international scientific literature on the current state of chestnut cultivation for fruit production in Germany is unavailable. Among the statistics of chestnut fruit production countries, Germany does not appear as a producer (Atlas Big, 2023; FAO, 2023). Therefore, the overall objective of this study was to fill this knowledge gap and explore the current state and future potential of chestnut cultivation as a perennial staple food crop in Germany. To do so, we (1) explored the characteristics of chestnut stands and their management in Germany; (2) evaluated the main motivations, aims, and challenges of chestnut growers regarding chestnut cultivation; (3) identified outcomes of chestnut production and measures for upscaling in Germany; and (4) analyzed differences between young and old chestnut growers. Finally, we discuss our results in the context of traditional and modern agroforestry systems, and the opportunities for Germany to integrate chestnuts as an element of sustainable food production.

Chestnut cultivation in Germany: history, utilization, and distribution

In Germany, chestnuts lost their significance as a staple food crop after the introduction of the potato in the 17th century (Ostermann and Hochhardt, 1993). By the end of the 19th century, industrial tannin extraction enhanced the need for chestnut wood, which increased the felling rates of chestnut trees. Industrialization of grain cultivation brought higher calorie output and implied a decrease in chestnut production (Conedera and Krebs, 2008). As chestnut poles for vineyards were substituted by wires and concrete or iron poles, demand for chestnut coppices declined rapidly as well. Lack of management led to a loss of valuable chestnut agroforestry landscapes, which developed into mixed forests with closed canopies that reduces fruit production (Bouffier, 2019). During the two World Wars demand for tannins and firewood was high and chestnut wood was also used for gun stocks, which led to over-exploitation. Simultaneously, fruits were used as food for armies and in military hospitals (Bouffier, 2018) and were also an important food source during after-war famines (Konold and Jotz, 2012). Through the change in eating habits after World War II, chestnuts lost their importance as a food source (Bender, 2002). Fungal diseases from Asia, such as chestnut blight (*Cryphonectria parasitica),* became a major driver of the chestnut decline in Europe (Wolpert et al., 2020). Chestnut blight has spread in Germany since 1992 (Wall and Aghayeva, 2014). Breeding and cultivation of chestnuts in Europe therefore should mostly rely on crossbreeding *C. sativa* with disease-tolerant Asian

chestnut species (*C. crenata* or *C. mollissima*) (Ecker et al., 2018).

During the past decades, chestnuts have experienced a revival and a renewed appreciation in other parts of the world, but recently also in Germany (Bouffier, 2019; Wolpert et al., 2020). This re-appreciation of chestnuts is not only based on the multiple products that chestnuts provide but also on their biodiversity values and cultural ecosystem services (Conedera and Krebs, 2008). *C. sativa* grows well in a yearly mean temperature of 8–15 °C and a minimum yearly rainfall of 600–800 mm (Conedera et al., 2016), on sites that do not have calcareous and/or water-logged soils (Ecker et al., 2018). In southern Germany, chestnuts reach an elevation of 700 m above sea level. Most of the chestnut stands in Germany are found in mature forests, and these have been estimated to amount to only 7500 ha (Bouffier and Maurer, 2009). Chestnut trees primarily planted for food production or ornamental reasons are found in gardens, parks, alameda, solitary trees, or groves (Bouffier, 2012). Areas known for chestnut trees are the regions Haardt and Dannenfels in Rhineland-Palatinate, the uplands Taunus in Hesse, and the mild climatic conditions of South-West Germany.

Methods

Survey design and data sampling

A social survey was designed to explore the status quo of chestnut cultivation in Germany, as a case study of perennial food crop integration in agroforestry systems. The survey was organized into three sections to compile information about (1) the personal background of chestnut growers and information on their chestnut trees, (2) motivation, aims, and challenges, and (3) growers' perception of ecosystem service outcomes and implementation of certain measures to upscale chestnut production and consumption in Germany. The detailed survey can be examined in Appendix 1.

In section (1) we gathered data on the personal background of chestnut growers including general questions such as age and profession. We also asked questions about the growers' relationship with chestnuts, such as whether chestnut cultivation is a family tradition and how respondents define themselves regarding chestnuts. We were also interested in the characteristics of chestnut stands including tree number, tree age, pest, and diseases as well as systems multifunctionality. We sampled the municipality and postcode to locate chestnut stands. In section (2) we asked respondents to name their three main motivations for managing chestnut trees. We also asked about the aims and challenges of chestnut cultivation by using predefined answer categories. For each answer category, we asked for the level of agreement on a Likert scale from 1 to 5 (1: fully disagree, 2: mainly disagree, 3: neither, 4: mainly agree 5: fully agree). In section (3), different ecosystem services were presented to respondents and then asked if they would associate the supply of these services rather with annual or perennial staple food crops or both (Likert scale; 1: annual agriculture, 2: rather annual agriculture, 3: both, 4: rather perennial staple food crops or 5: perennial staple food crops). We suggested measures for upscaling chestnut production and consumption and asked respondents about how easy they would think these are to implement (Likert scale from 1 to 5; 1: very difficult to implement to 5: very easy to implement) and which impact such a measure would have on increasing chestnut production and consumption (Likert scale 1–5; 1: very low impact to 5: very high impact). We always gave the option to add their answers to predefined answers for aims, challenges, outcomes, and measures.

The survey was pre-tested and subsequently improved with the help of three chestnut experts in Germany. The inclusion criteria for the survey participants were individuals who managed at least five chestnut trees for fruit production in Germany. We also included respondents whose trees had not yet produced fruit. We aimed to characterize all chestnut fruit growers in Germany. To identify possible respondents, we first approached our previous contacts and investigated the internet. We contacted the chestnut community of interest (Interessensgemeinschaft Edelkastanie), the German Association for Agroforestry (DeFAF), and different authors reporting about chestnuts as well as posted a request on social media chestnut groups. Further contacts were obtained using snowball sampling. We asked respondents if they knew other chestnut growers suitable for our survey. We identified 79 respondents who met the inclusion criteria. Potential respondents were contacted by phone to ask for their participation, and in case they agreed, to set an interview date. Interviews were conducted by F. Gaede by phone and recorded and transcribed after obtaining respondent informed consent. Each interview lasted between 30 min and 2 h. In twelve cases, we either could not reach the respondents or were unsuccessful in finding an interview date. A total of 67 interviews were conducted. Finally, three interviews were excluded because during the interview it became clear that respondents were not managing chestnut trees. Interviews were conducted from March to July 2022. We interviewed seven female and 57 male respondents.

Data analysis

Frequency analysis were used to analyze the section one on the characteristics of the respondents, and chestnut stands. Information about the main motivations to manage chestnut trees was analyzed through qualitative analysis. Responses were sorted to three main motivations according to similar meanings (e.g. beautiful tree, aesthetics -> aesthetics). In a second step, an inductive approach was used to group motivations according to similarities in 6 categories (Quintas-Soriano et al., 2023) (see Table 1). For these six motivation categories, we conducted frequency analysis, as well as for the information on personal aims, current challenges, perceptions of ecosystem services supply, and measures for upscaling. We did so to find out how many chestnut growers show which level of agreement regarding the Likert scale questions that were asked. Additionally, we calculated mean answers and standard deviations (SD). We then compared participant and chestnut stand characteristics between junior (up to 40 years old) and senior (older than 40 years) chestnut growers (Gullino et al., 2020; Zafeiriou et al., 2022) using the program SPSS (see Appendix 2). For nominal data, pairwise comparisons (Chi-square test) were applied. In cases where more than 20 % of cells had an expected frequency <5, we used a two-tailed Fisher's exact test to calculate the significance. Nonparametric statistical comparison analysis (Mann Whitney U) on ordinal data was used to reveal differences in responses between junior and senior chestnut growers for motivations, aims, challenges as well as perceptions on ecosystem services outcomes and measures for upscaling.

Results

Characteristics of growers, chestnut stands, and their management

The final social sample included a total of 64 chestnut growers, where 28 were defined as junior growers (up to 40 years; 44 % of the sample) and 36 as senior growers (aged above 40; 56 %). The youngest respondent was 24 years, the oldest was 77, and the average age of respondents was 45 years. The professions of interviewed chestnut growers were diverse. Respondents were identified as farmers/agricultural engineers (20 %), arborists (13 %), landscape planners/gardeners (11 %), and foresters (8 %). Some respondents professions were not connected to chestnut growing, such as scientists (9 %), professionals of the educational sector (7 %), electrical/metal engineers (5 %), medical doctors (3 %), one entrepreneur (2 %) and one economist (2 %). Most respondents defined themselves as hobby growers (42 %), while 16 % considered themselves farmers with chestnut as a line of business and 13 % as chestnut experts. No participant defined him/herself as a chestnut farmer and 30 % could not identify with any given category but added how they define themselves, such as agroforestry service provider, fruit grower, or chestnut devotee. Chestnut trees were managed by the respondent alone in 46 % of cases, with the family in 29 %, with employees in 17 %, in a community in 13 %, with other entrepreneurs in

Table 1
Respondent's motivations for chestnut cultivation. The percentage of respondents that named these motivations amongst three main motivations are given for each motivation. They are grouped into motivation categories.

Sustainable food production	Personal well-being	Multifunctional uses	Landscape restoration	Added value	Socio-cultural motivation
Climate change mitigation and adaptation [36 %] Alternative for annual agriculture [20 %] Subsistence [8 %] Regionality [6 %] Diversification of production [6 %] Resilience [6 %] Longevity [6 %] Orchard meadow conservation [5 %] Vital tree [3 %]	Aesthetics [22 %] Fun/pleasure [17 %] Gusto/taste [8 %]	Food production [23 %] Honey plant [9 %] Multifunctional uses [8 %] Wood [5 %]	Biodiversity [20 %] Multifunctionality for the environment [6 %] Shade [3 %]	Innovation [19 %] Marketing [6 %] Added value [3 %] Low maintenance effort [3 %]	Connection [8 %] Knowledge transfer [6 %] Food sovereignty [5 %] Awareness for transformation [3 %]

6 %, and as a scientific project in 3 % of cases. Most respondents had one to four contacts to other chestnut growers (64 %), therefore, we categorized them as being "connected". We found 30 % of respondents were isolated, which means that they did not know any other chestnut grower with five or more chestnut trees. Only 5 % of respondents we defined as well connected (5–9 contacts) and 3 % were very well connected (above 10 contacts). Senior respondents were more often isolated, whereas juniors were more often connected (r=−0.40, p<.05, Mann Whitney U). Only 22 % of participants specified chestnut management or eating chestnuts as a family tradition.

Both, respondents and the locations of their chestnut trees were relatively evenly distributed across Germany (Fig. 1). The type of systems described was very diverse: 81 % of respondents indicated to have also other tree species in their system, like apple trees, and 48% specified systems with shrubs included, e.g. hazelnut. While 70 % mowed the understory, 36 % kept livestock. In 17 % of cases, systems included vegetables, while annual cropping on the same field was specified by 16 %. Across age groups, junior growers more often grew vegetables (x^2=0.257, p<.05, Fishers exact) and had livestock grazing more frequently (x^2=0.250, p<.05, Chi-square) in comparison to seniors. Some growers had only 5 chestnut trees, the median number was 15 trees and one participant had 1000 trees. The majority of the trees (2066 out of 3278) were in the young age of 1–5 years. Most other trees were in the following age groups: 6–10 years (297 trees), 11–15 years (309 trees), 16–20 years (210 trees), 21–25 years (189 trees), and 26–30 years (181 trees). One participant with 1000 trees, who planted around 150 in each of the 5year-periods had a high effect on this distribution, as he is an outlier in chestnut number. While junior chestnut growers had more often younger trees, seniors tended to have trees in older age groups (r = 0.446, p<.001, Mann Whitney U). We found no significant differences in chestnut tree numbers across junior and senior growers (r = 0.061, p=.627, Mann Whitney U).

The land-use systems that included chestnut trees were diverse. Most chestnuts were part of orchard meadows/silvopastoral systems (56 %). Forest gardens and fruit home gardens were the land-use system of 17 % of the chestnut trees, while 14 % were part of silvo-arable systems. We

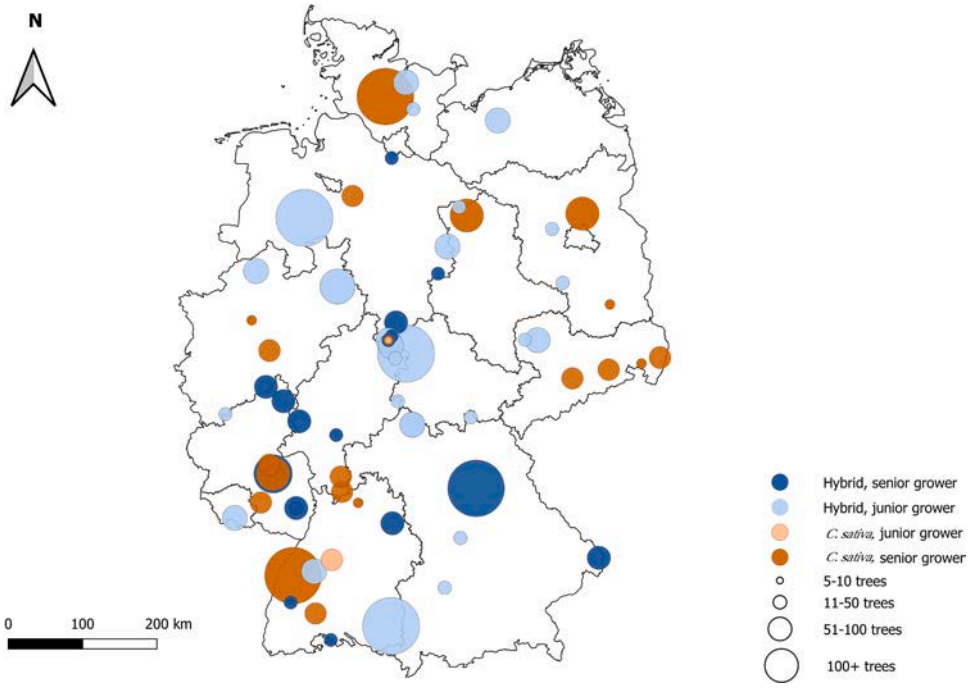

Fig. 1. Distribution of our respondents and their respective chestnut stands across Germany. The orange color shows respondents that have more or only pure C. sativa, while Hybrids with Japanese trees are indicated in blue. Color intensity indicates age group, where lighter color represents junior and stronger color senior growers. The size of spots indicates the number of chestnut trees (Smallest 5–10 trees, Second smallest 11–50 trees, Second largest 51–100 trees, and largest above 100 trees).

only found 5 % of respondents having monospecific chestnut plantations, 5 % other unnamed systems, and 3 % having chestnuts for food production in forests. Of our respondents, 28 % specified making multifunctional use of the side products of chestnut trees such as wood, foliage fodder, honey, or opportunity for education on chestnuts, including a higher number of seniors (x^2=0.256, p<.05, Chi-square). While 16 % of respondents found pests and diseases, they were more often prevalent in chestnut stands of senior growers (x^2=0.281, p<.05, Fishers exact). Currently, none of the respondents makes use of pesticides for chestnut cultivation or harvesting chestnuts with machinery. Regarding species choice, 63 % of growers planted more hybrid trees than pure *C. sativa*. In the junior group, we found statistically significant more growers that grow mostly hybrids (x^2=0.434, p<.001, Chi-square). Respondents planted in 19 % of cases seedlings from an unspecified origin, in 44 % of cases seedlings from a chosen genetic origin, and in 38 % of cases grafted trees. Seniors had more often seedlings of unknown genetic origin (x^2=0.390, p<.001, Chi-square), whilst juniors had more often seedlings with chosen genetics (x^2=0.343, p<.05, Chi-square). Regarding the yield of the chestnuts, only 17 % reported that their trees were already yielding. Yields varied between a few nuts from young trees to 20–100 kg of old trees. The average of the assumed duration of our respondents until chestnut trees become profitable is 11.74 years.

Motivations, aims, and challenges

The main motivations, named by the respondents regarding the cultivation of chestnuts, were climate change mitigation and adaptation (36 % of respondents), followed by food production (23 %) and aesthetics (22 %). An alternative for annual agriculture, which referred to growing a potentially more sustainable perennial staple food crop and biodiversity was named by 20 % of respondents.

After grouping motivations, we found that most motivations named were in the category of sustainable food production (73 % of respondents named at least one motivation we put in this category), followed by personal wellbeing (41 %), and multifunctional uses (36 %), landscape restoration (33 %), added value (28 %) and socio-cultural motivations (20 %). We found differences across junior and senior growers in three motivation categories: while juniors more often named motivations which we pooled in sustainable food production (x^2=0.238, p<.05, Chi-square), seniors were more motivated by personal well-being (x^2=0.270, p<.05, Chi-square) and multifunctional uses (x^2=0.258, p<.05, Chi-square).

The personal aims of the respondents regarding chestnut cultivation are illustrated in Fig. 2. The highest agreement was found for roasting chestnut fruits (mean 4.73, SD = 0.81) with 92 % having fully or mainly agreed. The second most common aim was fostering chestnut culture (mean 4.52, SD = 0.99) which was fully or mainly agreed upon by 89 %, followed by an increasing number of chestnut trees (mean 4.44, SD = 1.27). Processing chestnut fruits differently than by roasting, for example by cooking or baking (mean 4.11, SD = 1.44), selling fruits (mean 3.83, SD = 1.59), and earning money (mean 3.67, SD = 1.67) had the least agreement but still over 60 % mainly or fully agreed for all aims (77 %, 66 % and 62 % respectively). We found no significant differences in personal aims between juniors and seniors.

The current challenges of chestnut growers are depicted in Fig. 3. The highest-rated challenges were institutions lack appreciation for long-term investment (mean 3.78, SD = 1.62), with 66 % of respondents agreeing. Missing traditional connections to chestnut cultivation (mean 3.55, SD = 1.60), and too low yearly subsidies (mean 3.43, SD = 1.82) followed by nearly 58 % and 57 % of agreement respectively. Most challenges showed mean values around three. Generally, there were no significant differences in perceived challenges between junior and senior growers.

Ecosystem services and measures for upscaling

The provision of all mentioned ecosystem services were rather associated with perennial food crops than with annuals. Carbon fixation was clearly associated with perennial food crops (mean 4.71, SD = 0.52; Likert scale, from 1: clearly associated with annual crops to 5: clearly associated with perennial crops) followed by biodiversity (mean 4.70, SD = 0.49) and erosion prevention (mean 4.70, SD = 0.53). Other ecosystem services in decreasing order were air and water quality (mean 4.69, SD = 0.56), recreation (mean 4.61, SD = 0.63) and multifunctional uses (mean 4.24, SD = 0.89). Food production was the ecosystem service least explicitly associated by respondents either with annual or perennial crops (mean 3.38, SD = 1.28). The only differences in perception of ecosystem services were that seniors more often associated provision of staple food to annuals and less to perennials (r=−0.359, p<.05, Mann Whitney U).

Regarding the easiness to implement upscaling measures, respondents most frequently specified options such as cultivation guideline (mean 4.27, SD = 0.91), conduction of seminars (mean 4.19, SD = 0.91), and degustation events (mean 3.82, SD = 1.05). The highest impact was attributed to better funding (mean 4.48, SD = 0.83), breeding disease-tolerant trees (mean 4.37, SD = 0.83), lighthouse projects (mean 4.27, SD = 0.81), and producing a cultivation guideline (mean 4.27, SD = 0.77). Combining both questions (Fig. 4), the two most critical measures for upscaling seem to be a chestnut cultivation

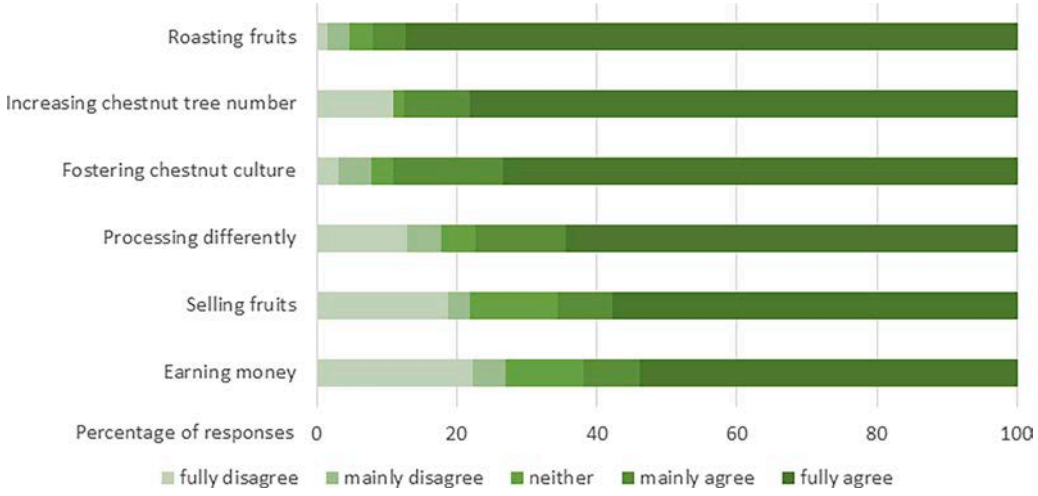

Fig. 2. Respondents' aims. Color intensity shows the rate of agreement percentage-wise.

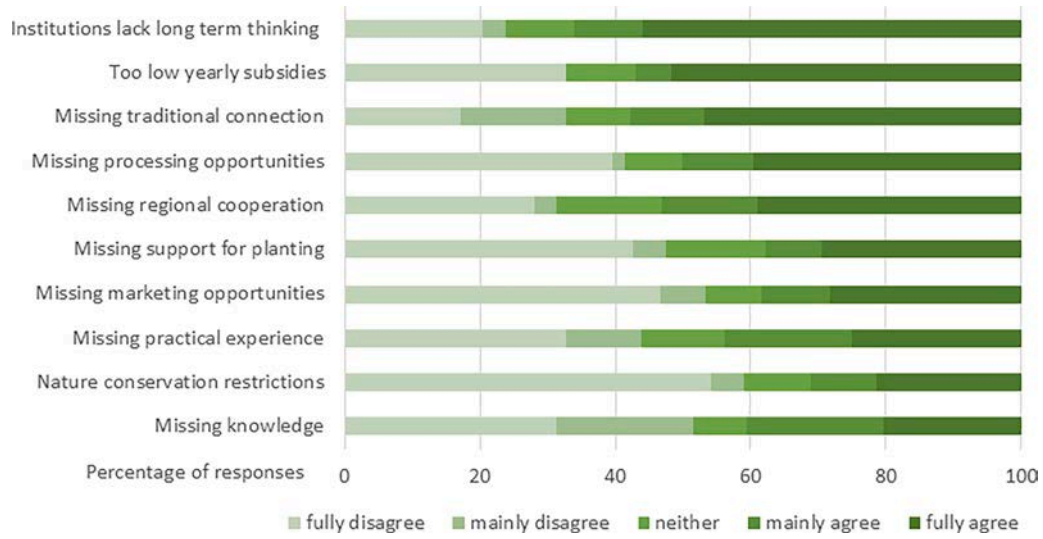

Fig. 3. Respondents challenges on chestnut tree cultivation in Germany. Color intensity shows the rate of agreement as percentages of respondents.

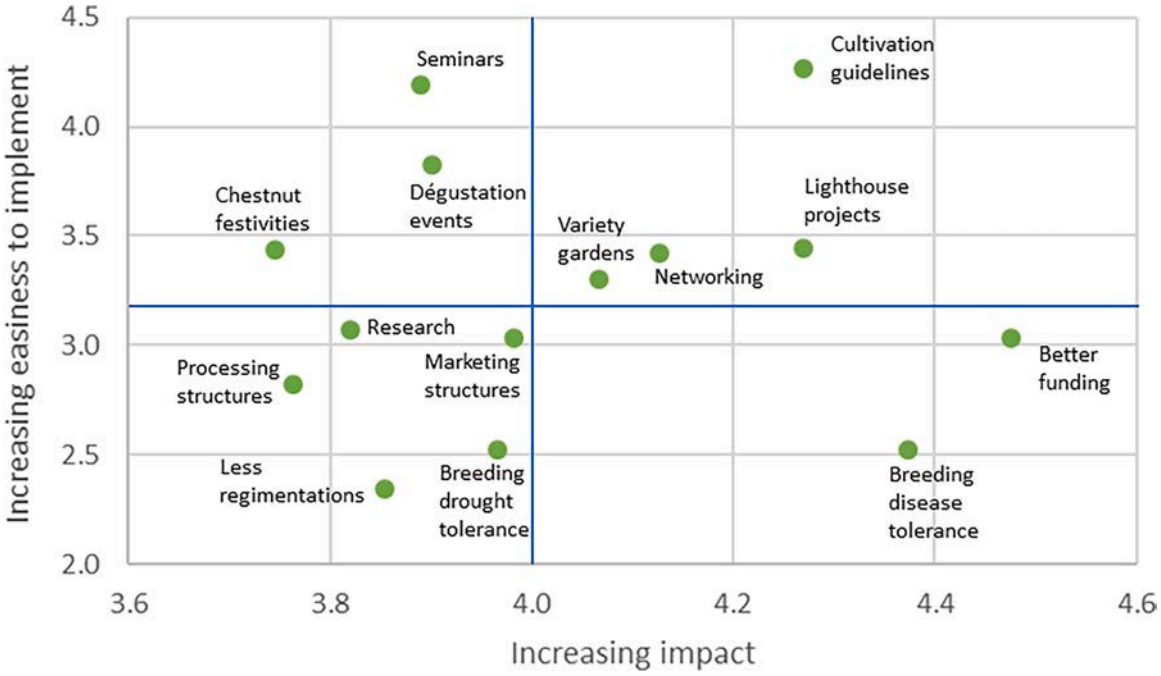

Fig. 4. Measures for upscaling chestnut production and consumption in Germany. Each of the respondents was asked to attribute each given measure a perceived easiness to implement (from 1 to 5; 1= very difficult, 5= very easy) and a perceived impact on upscaling (1= very low impact, 5 very high impact). The mean values of measures are depicted in green. The mean across all measures is indicated in blue lines to extract critical measures in the upper right quarter.

guideline (mean implementation 4.27, SD = 0.91; mean impact 4.27, SD = 0.77) and better funding schemes for chestnut production (mean implementation 3.03, SD = 1.31; mean impact 4.48, SD = 0.83).

Discussion

Characteristics of chestnut growers and stands

Our results showed that none of the participants was a professional grower that sells chestnuts. This is also reflected by the fact that Germany does not appear in statistics of chestnut-producing countries (Atlas Big, 2023; FAO, 2023). We found a high proportion of newly planted trees accompanied by a high motivation by respondents to increase their number of trees. This is not only the case in Germany, as the US for example also does not appear in the statistics on the world chestnut-producing countries but is listed as an emerging country for chestnut production by Biaggi et al. (2020). Compared to Germany, the US has already established commercial chestnut plantations that are yielding. Chestnut production as well as professional breeding programs are increasing in the US (Davison et al., 2021). We found twice as many hobby growers than farmers with chestnut production as one branch of business and not a single mainstay chestnut farmer so far. In the Apennines in Italy, Pezzi et al. (2017) found twice as many mainstay farmers as hobby farmers, in a region with a long tradition of chestnut cultivation (Wolpert et al., 2020).

Motivations and challenges

Chestnut growers were highly motivated and most of them aimed to plant additional chestnut trees in the future. By far the most often named motivation for cultivating chestnuts was sustainable food production. Interestingly, outstanding motivations in this category were climate change mitigation and adaptation as well as an alternative to annual food production. With our respondent́s motivation on climate change mitigation and adaptation, the most pressing topic of the last decades is touched (IPCC, 2019; Michler et al., 2018) In many cases the respondents said that they have been motivated to plant chestnut trees as it is a tree species that is expected to tolerate potential warmer and drier future climates. We were surprised by the high number of respondents that named an alternative to annual food production as a motivation. To us, it seems not yet to be a topic of public interest in Germany, although some studies have pointed to such potential (Kurth et al., 2019; Luo et al., 2010; Schwarzer, 2021; Willett et al., 2019). It seems that involvement with sustainable food production motivates people to plant chestnuts in traditional as well as modern food production systems. However, motivations for tree planting can be diverse and vary due to the context. In a study on the adoption of agroforestry in the southern Philippines for example, income and soil erosion prevention were major motivations (Magcale-Macandog et al., 2006). We found junior growers to be especially highly motivated by motives of sustainable food production compared to senior growers. Increased motivation of the younger generation could be a sign of increasing awareness of the negative outcomes of the current food system as well as of the need for a transformation of this food system. However, the meta-analysis of Hertel et al. (2013) could not find a clear overall relationship between age and environmental concern, values or commitment.

Our respondents attributed the missing traditional connection to chestnuts as being the third most important barrier to chestnut cultivation. Only about a fifth of respondents specified a chestnut tradition in their family including either cultivation or consumption. This finding is supported by Pezzi et al. (2017) who compared young peoplés interest in growing chestnuts and found that the ones with traditional chestnut cultivation in their family have a higher motivation than others to grow chestnuts. However traditions can also be abandoned because of greater challenges. In the Cevennes in France for example, which are known for their wide-spread chestnut groves, chestnut cultivation declined contemporary with rural depopulation because of the remoteness of the rural, the lack of opportunities for mechanizing harvest and maintenance, as well as missing workforce (Arnaud et al., 1997).

Interestingly, the highest scored challenge for respondents was missing long-term thinking of institutions. In the early 20th century already, Smith (1929) mentioned the lack of long-term thinking of institutions and policy-makers as a limitation to funding schemes for perennials, which was also noticed by Molnar et al. (2013). The time lag between establishment and returns of 6–10 years makes pre-investment necessary and therefore makes funding more important (Davison et al., 2021). However, if food would have a real prize including ecosystem services and disservices, food crops from perennials could be much cheaper than those from annuals (Kay et al., 2019).

Ecosystem services outcomes

Respondents associated ecosystem services more strongly with the chestnut/perennial food production system rather than the annual. Tsonkova et al. (2018) found that farmers recognize the environmental advantages of agroforestry, but claim to get additional support for the greater effort to maintain more complex systems. Additionally, the environmental disservices of annual agriculture such as soil erosion, biodiversity loss, and carbon emission are rarely included in product prices (Kremen et al., 2012), which act as a barrier to establish such multifunctional systems. Especially for carbon fixation and soil protection respondents advocated for chestnuts as a system that serves as a carbon sink. Carbon sequestration and enhanced soil health are also perceived as important agroforestry outcomes by farmers in Germany, found by Tsonkova et al. (2018). In a Europe-wide study, soil protection is one of the key objectives of respondents to plant trees on cropping land (García de Jalón et al., 2018). An improved water cycle was also repeatedly named as an ecosystem service, provided by chestnuts as perennials. Perennials improve water infiltration and reduce runoff, leading to better water availability for plants as well as groundwater recharge (Molnar et al., 2013). Besides food, chestnut trees provide other provisioning services like wood, leaves, and nectar. We found that more seniors use side products of chestnut trees, such as wood and honey. This can be traced back to the fact that they more often have older trees that already provide these products. Regarding multifunctional use of the site, more juniors grow vegetables and keep livestock at the chestnut system.

Biodiversity was also clearly attributed to perennial systems by our respondents and served as important motivation to cultivate chestnuts. Similar results were found in a chestnut study in Greece, where 94 % of respondents related an increase in biodiversity to agroforestry (Zafeiriou et al., 2022). In the Europe-wide stakeholder analysis named above by García de Jalón et al. (2018), biodiversity was the highest-ranked environmental outcome of agroforestry and was positively associated by more than 50 % of respondents. The transformation of annual crops to multifunctional agroforestry systems can increase biodiversity through an increase in structural complexity as well as in heterogeneity of habitat and landscape (Torralba et al., 2016).

Measures for upscaling

For upscaling chestnut cultivation in Germany, respondents identified improved funding as the most important measure. This can likely be traced back to the described time lag between the establishment and returns of tree crops. Although the implementation of improved funding as an upscaling measure was rather perceived as medium easy, political will could change it. Rules of the Common Agricultural Policy of the EU could provide funding for up to 80 % of the implementation cost of agroforestry systems including five years of maintenance through rural development support (Augere Granier, 2020). However, to date, most of the federal states of Germany do not support the implementation of trees in agricultural systems.

The second highest impact of a measure to scale up chestnut cultivation in Germany was associated with breeding disease tolerance. Diseases are an important driver of yield loss in countries that relied on *C. sativa* or *C. dentata*, besides the abandonment of chestnut groves through an aging population and industrialization of agriculture and the food system (Biaggi et al., 2020; Gullino et al., 2020). Some respondents planted grafted trees of known varieties, others planted seedlings of known varieties, and some planted seedlings from unknown genetics. Grafted trees ensure a certain nut quality because of clonal propagation, whereas breeding of good varieties and planting seedlings of them makes sense in terms of genetic diversity, especially in a world of unknown future climates and globally spreading pests and diseases that might evolve and crack a disease tolerance (Davison et al., 2021). Future research in nut quality of seedlings from different crosses is desirable. The fact that junior growers have significantly more hybrid chestnuts between *Castanea sativa* and *C. crenata* and/or *C. molissima* than seniors could show that the awareness of the impact of the diseases rose and/or that hybrid planting material is increasingly offered by tree nurseries.

A cultivation guideline was perceived as a measure having a high impact while being the easiest to implement, although knowledge about chestnut cultivation was only rarely specified as a challenge by our respondents. Research-based best practice guidelines were also identified as being a key need in the US to scale up chestnut production (Davison et al., 2021). Knowledge transfer in seminars and degustation events were regarded as further measures that are easy to implement. They would help people to get a cultural connection, which was an important

barrier for chestnut cultivation, according to our respondents. Lighthouse projects were further seen as one of the most impactful measures by our respondents. Chestnut cultivation seems to be in a phase in Germany where only innovative people grow them in a higher quantity. If they prove to be successful, others could follow, which would be also assumed following the theory of diffusion of innovations (Rogers and Shoemaker, 1971). Networking was also among the most critical measures. The better connection of junior growers among other growers in comparison to seniors could increase the easiness to implement this measure. Building multi-stakeholder networks to support farmers in the design, implementation, and management of agroforestry systems was suggested as a key strategy to scale up agroforestry by Louah et al. (2017).

We did not find any chestnut grower who defined themselves as a chestnut farmer in Germany and not a single professional, old and well-established yielding chestnut production site. However, the global chestnut market has been growing since 1990 (Biaggi et al., 2020) and has been expected to grow by a 2.2 % compound annual growth rate from 2018 to 2025 (Davison et al., 2021). Import in Germany in 2016 was 3400 tonnes (Biaggi et al., 2020) which in 2021 increased to 5024 tonnes (FAOSTAT, 2021). Due to climate change, some crops, like the chestnut, that currently grow in Southern Europe could become more suitable in Central and Northern Europe or higher elevation areas in Southern Europe (Freitas et al., 2021). By comparing the bioclimatic distribution area of chestnut trees with climate forecasts, such outlooks could be more specified and suggestions for favourable regions could be made for Germany, similar to the studies carried out for Portugal (Freitas et al., 2022) and for Turkey (Sarikaya and Örücü, 2019).

We found that most of our respondents had their chestnut trees as part of orchard meadows. However, the options for chestnut production are manifold: Chestnuts can grow on steep slopes, marginal farmlands, and degraded soils. They can be planted in home gardens, in forests, in edible landscapes, as alley trees along the road, as well as in towns and cities, where no staple food is usually grown (Molnar et al., 2013). However, fruit production is expected to better in thick, humus-rich soil with a higher water-holding capacity (Beccaro et al., 2020; Martins et al., 2010). High humus content and good nutrient availability seem to help chestnut trees to express tolerance against chestnut blight (Gonthier and Robin, 2020). In comparison to other tree crops chestnut trees have low labour costs (low pruning effort and nuts falling to the ground) and are a carbohydrate-rich staple food crop (Vasconcelos et al., 2010). A tree crop integration in annual cropping systems can combine high food production with a high ecosystem services supply. Due to the provision of a high carbohydrate food crop, chestnut trees seem to enable a food system transformation towards silvo-pastoral, staple food-providing agroforestry systems.

Conclusion

Little investigation has been carried out on chestnut fruit cultivation in Germany. This study is a first attempt to explore the potential of cultivating chestnuts as perennial staple food crops in Germany. We found that chestnut growers were rare, not professionalized, and scattered across Germany. We discovered a trend toward increasing numbers of chestnut plantings in the last 5 years and of most growers having plans to further increase their numbers of chestnut trees. Outstanding characteristics of chestnut cultivation were their multifunctional uses and their integration into diversified farming systems, such as orchard meadows, forest gardens, and annual cropping systems. Although motivations to cultivate chestnuts were diverse, the most common motivation was to sustainably produce food. Junior growers were even stronger motivated by sustainable food production and better connected among other chestnut growers, compared to seniors.

On the one hand, our initial research indicates the need to expand research in the field of chestnut cultivation, for example deepening knowledge on the motivations of chestnut growers, e.g. disentangle interacting intrinsic, instrumental and relational motivations to cultivate chestnuts. On the other hand, respondents frequently expressed the need for a quantification of the status quo and potential contribution of other perennial staple crops (such as acorn, walnut or hazelnut) to sustainable food systems.

Chestnut growers suggested a cultivation guideline, lighthouse projects, and networking as the most critical measures. Networking will help to exchange information and lighthouse projects can inspire further people to grow chestnut trees. For the implementation of all these measures, a cooperation of scientists with chestnut growers in Germany and abroad would be useful. Additionally, better funding schemes were regarded as being the most influential measure to transform food production landscapes into multifunctional ecosystems with positive social-ecological outcomes. True prizes would also foster chestnut and other tree crop production as they also account for ecosystem services or disservices. These are measures that should be realized in politics.

CRediT authorship contribution statement

Franziska Gaede (b. Wolpert): Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Cristina Quintas-Soriano:** Methodology, Supervision, Validation, Writing – review & editing. **Bill Davison:** Supervision, Validation, Writing – review & editing. **Tobias Plieninger:** Supervision, Validation, Writing – review & editing.

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

The data has been uploaded on the data repository zenodo and is available at zenodo.org/record/7,831,467

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.tfp.2023.100473.

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