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Masterarbeit

Thema: **Citizen Science-basierte Erfassung ungewöhnlich alter starkwüchsiger Apfelbaum-Unterlagen und ihrer Standortbedingungen als genetische Ressource für Klimawandel-angepasste Apfelunterlagen**

Topic: **Citizen-science-based assessment of unique, old and vigorous apple rootstocks and local growing conditions as genetic resources for climate change adapted apple rootstocks**

im Studiengang Angewandte Nutztier- und Pflanzenwissenschaften
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Vorwort

Der Klimawandel ist eine Bedrohung unserer Lebensgrundlagen, die wir nur gemeinsam bewältigen können. Mein Dank gilt daher denen, die sich aus der Notwendigkeit einer noch nicht ausreichend klimabewussten Agrarpolitik heraus uneigennützig für eine klimaresiliente Land(wirt)schaft einsetzen: Ich bin dankbar für das großes Interesse und Bereitschaft der freiwilligen Bürgerwissenschaftler:innen, dieses Projekt mit Interesse und ihren Beiträgen zu unterstützen. Meine Bewunderung gilt dem Pomologenverein und seinen Freund:innen, für ihre unermüdlich und unschätzbar wichtigen Arbeit und Leidenschaft, auch in der Unterstützung dieses Projektes. Ich bedanke mich bei dem Kooperationspartner dieser Arbeit, der Baumland-Kampagne, welche mit Umsicht und Entschlossenheit dafür kämpft, dass Agrargehölze wie Agroforst, *Streuobst* und Obstallee ein untrennbarer Bestandteil einer klimaresilienten Landschaft werden. Meine Freude möchte ich darüber ausdrücken, bei dieser Arbeit von Anna-Lea Ortmann und Prof. Dr. Kathrin Deiglmayr begleitet worden zu sein, welche mir zur Seite standen und mir immer wieder lohnenswerte Perspektiven aufzeigen konnten.

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Preface

Climate change is a thread for livelihoods of humankind, that can only be overcome in cooperation with each other. I give thanks to those, that are investing themselves selflessly towards climate resilient (agricultural) landscape driven by the imperative necessity imposed by a course of agrarian politics that is still inadequately addressing climate change. I am thankful for great interest and willingness of the citizen scientists supporting this project with their interest and contributions. My adulation for the German association on pomology and their supporters, for their tireless and invaluably work and passion, also by supporting this project. I give thanks to the cooperation partner of this thesis, Baumland-Kampagne, that is campaigning thoughtful and determined to get woody plants as agroforestry, *Streuobst* and fruit tree alleys involved inseparably into a climate resilient landscape. I would like to express my delight in being supervised in realizing the present work by Anna-Lea Ortmann and Prof. Dr. Kathrin Deiglmayr, that were supporting me and pointing out worthy perspectives repeatedly.

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RCP	Representative Concentrtion Path
DWD	German Weather Service – Deutscher Wetterdienst
IPCC	International Panel on Climate Change
CO_{2eq}	Equivalents of Carbon dioxide for other greenhouse gases regarding greenhouse effect
e.g.	For example …
AMOC	Atlantic Meriodional Overturning Circulation
NAC	North Atlantic Current
C	Elementary Carbon
ARD	Apple Replant Disease
NIAB	National Institute of Agricultural Botany
Cf	Latin *conferatur*, meaning "compare…"
GDPR	General Data Protection Regulation of the European Union
CRS	Coordinate Reference System

Abstract

Standard apple trees could become a vital part of a climate resilient, food secure agriculture in Germany and neighbouring countries, populating traditional or modern agroforestry systems. Vigorous growth and high stems are induced by vigorous rootstocks. Rootstocks are playing an important role in the whole tree's ability to adapt to climate change conditions. A temporal gap in research and development concerning vigorous apple rootstocks is contemporarily resulting in both a reduced diversity in vigorous rootstock market availability and the beginning impoverishment of genetic variability. The present project was reviewing literature to gather requirements imposed on climate resilient vigorous apple rootstocks. Requirements were characterized by plurality, reflecting diverse use cases and uncertainty in predictions of future climate change impacts. Inspired by an engaging voluntary network of German fruit tree enthusiasts, a citizen science approach was designed to enable advanced participants to geo-reference and assess approximately 100-year-old "veteran" apple trees' traits and belonging local conditions, which can indicate climate resilient rootstocks. A digital assessment protocol realized in the online form builder *jotform* was embedded into a citizen science. The data collected during three months of tree data collection was augmented with local annual rainfall, altitude, and the water retention index. Explorative data analysis indicates that the assessed trees expressed a wide variability and grew under diverse conditions, now allowing a selection of candidates for future studies let by criteria. Data to evaluate the utilized citizen science approach suggests, that simple mass approaches and elaborate assessments with trained and advanced participants could be combined in an extended or continuous assessment of veteran apple trees to improve data quantity and quality. Concluding the project with a final evaluation and assuring data usability by deploying a secure database format is planned for the near future.

Zusammenfassung

Hochstämmige Apfelbäume könnten in Deutschland und benachbarten Ländern unverzichtbarer Teil einer klimaresilienten, Ernährung sichernden Landschaft werden, in der sie in traditionellen und modernen Agroforstsystemen wüchsen. Starkes Wachstum und Hochstämmigkeit werden von starkwüchsigen Unterlagen induziert. Veredlungsunterlagen spielen eine wichtige Rolle in der Fähigkeit des ganzen Baumes, sich an die Bedingungen des Klimawandels anzupassen. Eine zeitliche Lücke in Forschung und Entwicklung hinsichtlich starkwüchsiger Unterlagen resultiert heute in verringerter Marktverfügbarkeit starkwüchsiger Unterlagen und einer beginnenden Verarmung der genetischen Variabilität von starkwüchsigen Unterlagen. Das vorgelegte Projekt sichtete Literatur, um Anforderungen an klimaresiliente starkwüchsige Apfelunterlagen zu sammeln. Diese Anforderungen zeichneten sich durch große Vielfältigkeit aus, welche die vielfältigen Nutzungsansprüche von Apfelunterlagen ebenso widerspiegeln wie die Unsicherheit der Vorhersage von Klimawandelfolgen. Das engagierte ehrenamtliche Netzwerk deutscher Pomolog:innen gab den Anstoß zur Entwicklung eines bürgerwissenschaftlichen Projektes, um fortgeschrittene Teilnehmende zu befähigen, etwa 100 - jährige „Methusalem“-Apfelbäume zu georeferenzieren und ihre Eigenschaften sowie Standorteigenschaften zu erfassen, deren Ausprägung auf klimaresiliente Unterlagen hindeuten können. Ein digitaler Erfassungsbogen wurde im online Formular Entwickler *jotform* umgesetzt und eingebettet in ein bürgerwissenschaftliches Rahmenkonzept. Daten welche im dreimonatigen Zeitraum der Erfassung gesammelt wurden mithilfe von Rasterdaten um lokale jährliche Regenmengen, Höhenlage und den *water retention index* ergänzt (Vandecasteele et al. 2018). Die explorative Datenanalyse lässt vermuten, dass die erfassten Bäume eine große Variabilität ihrer Eigenschaften und Standortbedingungen aufwiesen, was nun eine kriteriengeleitete Auswahl von Kandidaten für die zukünftige Untersuchung ermöglicht. Daten zur Evaluation des genutzten bürgerwissenschaftlichen Ansatzes deuten darauf hin, dass simple Ansätze mit Massen-Beteiligung mit komplexeren Ansätzen zur Erfassung durch fortgebildete, erfahrende Teilnehmer:innen kombiniert werden sollten. Gemeinsam mit einer verlängerten oder andauernden Erfassungsphase der „Methusalem“-Apfelbäume könnte dies die Datenqualität und -quantität verbessern. Der Abschluss des bürgerwissenschaftlichen Projektes inklusive abschließender Evaluation und Bereitstellung der Daten in einem sicheren Datenbankformat ist für die nahe Zukunft geplant.

1. Introduction

1.1 Relevance

Importance of standard fruit and apple trees in agriculture and landscape of Germany

The apple fruit is of great importance in Germany, no fruit is consumed in greater amounts per capita (Statista 2024a). On the European level, apples fruits are of growing economic importance (Muder et al. 2022). The great cultural relevance of apples is stressed by Juniper; Mabberley (2022).

Contemporarily, vigorous, standard fruit and apple trees are mainly found as a part of meadows with scattered fruit trees, fruiting alleys or in private gardens (Juniper; Mabberley 2022).

Their economic relevance is declining in the European countries, with intensively farmed systems providing the major share of a growing number of freshly consumed apples (Muder et al. 2022).

Meadows with scattered fruit trees, referred to as *Streuobst* throughout this thesis, is recognized as intangible cultural heritage by UNESCO (United Nations Educational, Scientific and Cultural Organization) since 2021, a status that was enforced with different NGOs and strong public interest (Degenbeck 2021). *Streuobst* is understood as a traditional agroforestry system (Klimke; Zengerling 2025) that emerged in Europe in the 18th century, with roots laying in the Roman Empire (Dagar; Tewari 2017). They are traditionally planted with standard fruit trees, that are long living, robust and can be integrated in the cultivation of arable farming or pastures, to produce hay or feed cattle directly – possible due to their long stem and highly attached crown. Traditionally, their ubiquitous existence for self-sufficient fruit production led to an immense variety of different cultivars, that were often specific for each region (BZL 2020).

Existing and cultivated *Streuobst* meadows can be understood as living (on-farm) preservation of genetic resources and is associated with high costs of the extensive production and maintenance practices (Begemann; Vögel 1995).

The different ecosystem services of intensified, commercial fruit plantations and traditionally managed *Streuobst* meadows were lately described by Reinke and Schlitt; Kramer in 2024, using the internationally applicable framework Common International Classification of Ecosystem Services (CICES). Schlitt; Kramer calculated the monetary yield of one specific area of *Streuobst* with different sorts of fruit trees to be more than 160,000 € per hectare in 10 years, assuming a base rate of 2 %. They highlighted, that only provisioning services will be object of trade, while services like “preserving ground water”, “preserving biodiversity” or “supporting education, leisure and aesthetics” are mostly not commodified and won’t translate into monetary yield for the tree’s owners.

Reinke compared ecosystem services of traditional *Streuobst* to modern, intensified fruit crop production and concluded, that the former was providing more regulatory ecosystem services (e.g.: hosting biodiversity, regulating water household, regulating pests by accommodating their natural antagonists) as well as cultural services, like aesthetics and room for recreational activities or education. Falkenburger Juni 2018 indicated *Streuobst's* values for pedagogy in their thesis and Zucchelli et al. 2022 reported on the societal mediation connecting urban to rural places, that is represented by these traditional habitats. On the other hand, Reinke 2024 found intensified fruit crop production sites to be stronger in producing products that are commodified, mainly food.
Another major difference between extensively grown *Streuobst* and fruit plantations is the longevity. *Streuobst* is developing it's unique ecological value while growing up to 100 years old beyond (Reinke 2024).
Beside extensively managed forests, *Streuobst* and (fruit) tree alleys are effectively buffering forest habitat loss by serving as surrogates, offering a wide diversity of different herbaceous and woody plants. Meaning, they are providing a very important service in regards of preserving biodiversity, some of them accommodating several thousand species (Wirth et al. 2024).
Streuobst sites are also producing vast amounts of fruits for processing, mainly for juices. In 2024, about 500.000 tons were estimated for the whole of Germany (VdF e.V. 24/07/2024).

Špulerová et al. let farmers of traditional fruit orchards fill out a questionnaire in 2025, to capture their view on the significance of the habitat and production site they were managing. Farmers from Czechia, Germany, England, Italy, Slovenia, Slovakia responded with:

- fruit production
- genetic diversity
- cultural benefits (recreation and social life)
- attributes appreciated for tourism
- ecological significance
- regulatory ecosystem services
- soil stabilization/ erosion control
- production of fruit and alcoholic beverages
- importance as priority habitats (esp. veteran trees)/ landscape features for biodiversity
- historical value/representation of traditional orchard regions
- community benefits

(Špulerová et al. 2025, p. 9)

Agroforestry

Standard apple trees can be valuable components of modern agroforestry systems, with great potentials for food security, biomass production, ecology, water use efficiency, carbon sequestrations and rural livelihoods (Zahoor et al. 2021; Hummel 08.09.2016; Lehmann et al. 2020; Zhao et al. 2022).

To build climate resilience, the agricultural sector could foster living structures in the arable landscape, like hedges, patches of forest, hedgebanks, creeks, modern agroforestry systems and permacultural practices. These structures will help limiting erosion, nutrient leakage and improve conditions for important pollinators as well as help holding water in the landscape to release pressure from groundwater bodies (Martina Flörke et al. 2024) and buffer microclimate in extreme weather situations. Supporting and protecting forests and Agroforestry systems is a way of managing risks of climate change by stabilizing and regulating. In other words: (Diverse) Agroforestry systems are a sustainable, but still intensive farming practice, that is providing several ecosystem services, including an efficient food and primary materials production, while additionally sequestrating carbon in perennial plants and soils and protecting biodiversity of many taxa and linking different ecosystems to each other (Brasseur et al. 2023; Lauri et al. 2022; Lehmann et al. 2020; Wirth et al. 2024).

Kay et al. calculated in 2019, that by harnessing a wide range of different agroforestry systems, a maximum of 234,8 million t CO_{2eq} could be sequestrated, focussing only on the prioritized regions of Europe every year.

For farmers, planting of standard fruit trees provides and additional financial investment in the future, as fruit trees are producing a fine wood, that can be sold for a good price (Hummel 08.09.2016).

The German professional association of agroforestry (Deutscher Fachverband für Agroforstwirtschaft, DeFAF) is therefore at the frontline of developing best practice models of future agroforestry systems and modern and innovative *Streuobst* cultivation (DeFAF 2024).

Traditional Agroforestry systems like *Streuobst* just as modern Agroforestry systems are considered to be a valuable option to adapt European agriculture to climate change conditions by pursuing complementary goals of diversity and multifunctionality in agriculture (Frei et al. 2020; IPBES 2024; Plieninger et al. 2020) – anyway, they are still rare in many European countries and the plantings of agroforestry systems are still hampered by barriers in underfunding, knowledge availability and acceptance (Baumgarten et al. 2024; Klimke et al. 2024; Wulff 2023; Klimke; Zengerling 2025).

Political context

Reports released by governmental institutions and agencies, European and national action plans, funding schemes and federal actions seem to be increasingly addressing the values of Agroforestry systems, both modern and traditional. The appreciation of woody plants values is implicitly encircling fruit and apple trees, that are playing a key role in some of these systems. Important examples are listed below:

Agroforestry’s potential to reduce greenhouse gases in Germany was estimated to be 2.08 million tons of CO_{2e} until 2026, solely resulting from the German annual funding for agriculture (“GAP-Direktzahlungen”) (Umweltbundesamt 2023). Traditional *Streuobst* is not covered by the definitions that allow farmers to apply for this fund.

Agroforestry systems are also playing an important role in the German “Aktionsprogramm natürlicher Klimaschutz – ANK” (=“program of natural climate action”), mainly highlighting, that linear structures of woody plant species are aimed to be multiplied in the future, to capitalize on their vast potential of mitigating and adapting to climate change and biodiversity loss (Öko-Institut, Berlin 2024).

Multiplying elements with woody species in agricultural landscapes in general, is playing an important role in European and German strategies to counteract biodiversity loss: Hedges and agroforestry systems are explicitly named as examples in the European *regulation on nature restoration* (European parliament 29.07.2024).

Their importance is also highlighted in the German national strategy for biodiversity 2030 in goal 8.2: “advance of landscape- and structural elements” (“Zunahme von Landschafts- und Strukturelementen”), naming hedges, tree rows and solitaire trees first in a row of examples and explicitly highlighting the importance of these structures and furthermore, of *Streuobst* and modern agroforestry systems for mitigation of soil erosion, regulation of hydrologic balance and local climate as well as protection of ground water from nutrient leakage. (BMUV 2024, p. 48)

The strategic goal of Germanys plan to implement the collective agrarian politics of the EU was aiming for 200.000 ha of agroforestry systems until 2027 when first published in 2022. After being evaluated as not achievable, the goal was 2024 lowered to 11.500 ha until 2027 (Bessert 25.04.2024).

Overall, the importance of *Streuobst* meadows for Germanys genetic resources, biodiversity, aesthetics and recreation, even health and pedagogy or education are widely, acknowledged by associations, institutions and politicians visibly for example in LfL Agrarökologie 2016 and BZL 2020.

Climate change related threats affecting standard fruit and apple trees

Unfortunately, *Streuobst* became rare in Germany and other European countries (Špulerová et al. 2025). Many threats for European apple production in general are imposed by climate change and can already be witnessed, for instance, fluctuating yields due to extreme weather events (Muder et al. 2022).

Experts are expecting and already witnessing a decline of the fitness of the remaining *Streuobst* meadows. Negative impacts on the extensively maintained standard fruit tree's vitality and even more the meadows profitability are foreseen to increase due to new and existing pests thriving in the warmer climate and the tree's being more vulnerable due to abiotic stresses – like heat, drought or excess water supply in winter (Göding 2021).

Nevertheless, there are young enterprises and initiatives advancing, that are trying to make a living from *Streuobst* with standard fruit trees. It is believed, that only an economically cultivated *Streuobst* meadow, that is not disadvantaged in the federal funding scheme, is able to unfold it's potentials (Degenbeck 2021).

Summarizing the most important impacts of climate change on the global, European and German level: The AR6 synthesis report of the International Panel on Climate Change (IPCC) is summarizing the dramatic, humanmade changes of global climate and the urgent need to take fundamental action to secure life of humanity on our planet. Reducing amounts of CO_{2eq} released into the atmosphere and fostering carbon sinks, are crucially needed (IPCC 2023).

The 2024 annual climate summary is reporting the first year with „an average temperature exceeding 1.5 °C above the pre-industrial level", and records for greenhouse gas levels, air temperature and sea surface temperature were broken. Overall, the data is "highlighting the accelerating impacts of human caused climate change" (Copernicus Climate Change Service 2025, p. 1). Copernicus climate change service is providing profound knowledge about the ongoing climate crisis and impacts on the European continent.

Climate change indicators in Germany are summarized by Statista 2024b as well, showing a rising annual mean temperature between 1960 and 2024 and an increase in annual heat days (defined as more than 30 °C) for every season, along with unprecedented low moisture in the top soil layer in the most recent years. Health of trees is documented to be decreasing since 1984, with about 10 % more trees being in bad conditions and the count of trees in good condition shrinking by more than 20 % - estimated by the density of their canopy (Statista 2024b).

Shortages of groundwater are increasing in Germany and impacting agriculture and natural habitats mainly when droughts are occurring. Main underlying reasons in Germany are overexploitation by excess use for drinking water and for industry uses. Further shrinking of the groundwater bodies is expected for every RCP (Representative Concentration Path) scenario, based on models provided by the German weather service, DWD (BGR 2024).

Not only overall means, but also patterns of weather are expected to change in the warming future: Occurrence and transition probabilities of omega and high-over-low blockings are altered in the Euro-Atlantic region, making persistent high pressure areas with heat and drought more likely, as well as persistent low pressure areas with ongoing, severe precipitation. In short: The weather pattern is likely to be more alternating and extreme (Detring et al. 2021).

Rising sea levels are also impacting Germany, with large areas at the coast lines and around the rivers Elbe, Weser and Ems being projected to be below the level of the annual flood in 2030. One of the largest areas of fruit production, Altes Land, is affected as well, as it is located close to river Elbe (Climate Central 2024).

Soil quality is expected to decline under climate change conditions on a global scale, with soil microbiome playing a pivotal role, but not being fully understood in its full complexity, yet. Land use change and climate change as impacts on the soils microbiome are still relatively unexplored (Jansson; Hofmockel 2020).

Soil salinity is expected to become an increasing problem worldwide, when soil water contents are reduced and sea levels are rising (Corwin 2021; Brasseur et al. 2023).

German soils fertility, functions and biodiversity are suspected to decline as well As the actual impact strongly depends on regional circumstances, like soil type, weather and climate predictions and land use, modelling of soil development under climate change conditions must be evaluated on a regional scale (Brasseur et al. 2023).

Climate change is altering future conditions on a regional specific basis. Some regions, like regions close to Magdeburg, called Magdeburger Börde and the Thuringian basin, that are already suffering from scarcity of precipitation, will additionally have to cope with the trend of less rain during summer time and more rain in winter time, as well as irregular weather patterns with extreme precipitation events. Overall, models are projecting higher temperatures in summer and winter, less rain in summer, but more rain in wintertime, instead of snow. Alongside, an increased risk of thunderstorm and hail is caused by high humidity in the atmosphere (Brasseur et al. 2023).

The Climate Service Center is providing information for different regions to allow them to adapt according to their site-specific prediction. Anyway, modelling of climate change scenarios on a regional level is very complex and depending on ongoing political decisions that are made nowadays. Therefore, local preparation for a variety of cases is needed. (Bender; Groth 2017)

Germanys neighbouring states are facing similar challenges in general (Jandl et al. 2024) and regarding apple production, e.g. Austrian traditional meadows with scattered fruit trees, with favourable regions for *Streuobst* production shifting in higher altitudes due to heat and water scarcity (kajtna et al. 2023). Mediterranean countries are expecting insufficient chill portions to fulfil the chilling requirement of apple trees. Sufficient chill is crucial for normal flower bud induction, leaf development, blooming and fruit setting, thus for economic fruit production. (Legave et al. 2016).
In Switzerland, climate change is causing phenological shifts, which is then affecting broad-leaved trees with droughts at low elevations (Meier et al. 2021).

Dramatic changes of the Atlantic Meriodional Overturning Circulation (AMOC) appear to be possible within the upcoming decades. The AMOC is driving the North Atlantic Current (NAC), that is transporting tropical warm water to the European continent. A potential collapse of the AMOC is predicted by different models, some of them suggesting, that a collapse could already happen in the middle of the 21st century. In 2024, Rahmstorf was pointing out that early warning signs of a collapse were found, referring to van Westen et al. 2024. The potential collapse, even though it is expected to happen over a period of one to several decades, is a serious thread for the European continent, as it would cause a drop of mean temperature, comparably to a little Ice Age, causing a disruption of precipitation patterns and an expected increase of precipitation in general. A scenario like that is even more likely, taking into account the missing political will to pull up climate action, as Rahmstorf was adding in an interview (Deutschlandfunk.de 30/06/2023).

Food security already is on stake on a worldwide scale. Disruption of food productions sites in different regions are already taking place and are expected to be multiplied in the future, with a higher frequency of extreme weather events being the main reason (Kopeć 2024). Food prices are expected to inflate globally. While countries in lower latitudes being especially vulnerable for negative impacts on crop yields, Europe will be affected as well, additionally due to it's global trading network (Shamshad et al. 2024) and dependency on fruit imports, for example. The German level of self-sufficiency for fruit crops being at about 20 %, for apples at 50 %, reveals a potential vulnerability, as the country could not serve the current demands of the public without fruit imports (Bundesinformationszentrum Landwirtschaft 2025). German fruit imports are strongly dependant on countries of lower latitudes (Garming et al. 2024).

The role of plant genetic resources in a changing climate

When theoretically matching future climate scenarios for different regions of the world with ecosystems associated boundary conditions, a shift of the global distribution of ecosystems can be expected (Smith; Smith 2012). Responses of different species under changing circumstances are not well understood, yet, which is hampering clear predictions for single species or ecosystems (Zettlemoyer; Peterson 2021).

This also holds true for agroecosystems, that are producing food, hence, climate change is putting food security at high risk, if genetic resources, that are currently preserved or in use as plant varieties, are failing when confronted with altered climate conditions. Biodiversity and availability of a vast range of genetic resources to use directly or for breeding, is providing safety and can allow humanity to adapt to climate change as good as possible. Preserving and enriching collections of genetic resources, especially of crops that are relevant for human nutrition, is therefore of outstanding importance to build climate resilience in the agricultural and food sector (FAO November 2011; IPBES 2024; Waqar et al. 2024).

But: As a result of an intensified agriculture and silviculture (forestry), German landscapes were homogenized in the recent century, widely losing their ability to support a rich biodiversity of flora and fauna (Wirth et al. 2024). Intensified agriculture, including monotonous crops, is considered the main driver of biodiversity losses. The agricultural landscape was historically supporting more biodiversity, not solely, but also by including woody species in the agricultural landscape (Sponagel et al. 2025). These impacts have also begun eroding biodiversity of fruit trees and fruit tree rootstocks, although their genetic resources had only seen mild genetic bottlenecks via domestication in the last few centuries (Gross et al. 2014).

Due to their extensive outcrossing, fruit tree cultivars are mostly propagated by grafting on rootstocks (Hanke; Flachowsky 2017).

To adapt apples trees to climate change conditions and new growing systems, suitable rootstocks are urgently needed (Martínez et al. 2024). As allelic diversity is necessary for breeding programs. (Korban 2021), building climate resilience in fruit crops is strongly dependant on accessions of genetic resources that are suitable to support a wide range of future scenarios and challenges that are imposed to rootstocks (Flachowsky; Töpfer 2021).

When considering dwarfed apples for apple plantations, “Most dwarfing rootstocks perform poorly in hot, dry climates” (Richard P. Marini; Gennaro Fazio 2018), but science and breeders are after all aware of the thread and research and development for the comparably important fruit industry is undertaken (Rangare 2024).

Contrarily, rootstocks for use cases in *Streuobst* or fruit-based agroforestry systems, that are supporting standard sized apple trees, have not been the objective of breeders for a long time and thereby specifically applicable genetic resources are rarely collected or well-known, as it will be described in the “state of research” section below.

1.2 State of research

The apple rootstocks impact

Grafting of fruit trees onto rootstocks is allowing a true to type propagation and additionally altering the resulting compound organism’s traits (Büchele 2018).

Mudge et al. were reviewing the history of grafting in 2009, summarizing the uses of grafting as: vegetative propagation, avoidance of juvenility, cultivar change, creation of unusual growth forms and repair, size control, biotic and abiotic stress resistance, transfer of infectious agents and physiological studies (Mudge et al. 2009).

The state of research concerning the impact of apple rootstocks onto scions and the compound organism is described below:

Altering of the whole tree’s physiology

Influencing the vigour, shoot growth and eventual size, both as height and volume, of the apple tree by choosing from different rootstocks that are greatly impacting the trees water relations by their specific hydraulic conductance and stem water potential can be considered the most obvious alternation of the tree’s traits (Casagrande Biasuz; Kalcsits 2022; Link 2007; Dhurve et al. 2023; DeJong 2022). But beyond that, stomatal conductance, leaf C isotope composition, water status of the whole plant and net gas exchange also seem to be involved in the growth reduction that is induced with dwarfing rootstocks (Casagrande Biasuz; Kalcsits 2022).

In experiments conducted by Abdalla et al. 1982 , rootstocks were influencing the nutrient composition of the leaves as well as the yield, with fruit yield being correlated negatively with the trunk cross-sectional area.

Probing 4 different rootstocks of increasing vigour: 'Budagovsky 9', M.9 Nic 29 (RN29), 'Geneva 30' (G.30) and 'Supporter 4', their influence on yield efficiency, leaf area, fresh and dry weights, leaf mineral content, as micro- and macro-elements, and photosynthetic efficiency was documented by Fallahi et al. 2013.

Rootstocks were found to influence gene expression of grafted scions in a rootstock specific pattern, that could be distinguished from patterns caused by other rootstocks (Jensen et al. 2010) and by altering the hormone flux, rootstocks were also found to be involved in regulating crop load and regularity of bearing (Kviklys; Samuolienė 2020). Thereby, rootstocks are indirectly impacting fruit quality traits like fruit size and weight, maturing, fruit firmness and starch contents via the linkage between numbers of fruit per tree and so called “crop density” – defined as fruit per cm^2 trunk cross-sectional area (Richard P. Marini; Gennaro Fazio 2018).

Phenolic contents of apple leaves were altered by the rootstocks, with semi-vigorous rootstocks causing significantly higher phenolic contents than less vigorous types. Phenolics are associated with many regulatory and stress associated reactions in plants (Yıldırım et al. 2016).

The ratio between apples vegetative and generative growth, sap flow and transpiration were influenced by the combination of rootstock and scion in experiments in a hot, semi-arid climate of the western plains of Albania(Domi et al. 2014).

Richard P. Marini; Gennaro Fazio 2018, p. 206 is offering an overview on scions growth and underlying mechanisms, differentiating induced and inherent traits of interest concerning rootstocks.

Altering of tree’s reaction on biotic factors

Roostocks are showing different levels of fine roots growth, which was found to have an impact on the tree’s tolerance for apple replant disease (ARD), a “soil born disease that affects young apple trees in many replanted orchards around the world” (Atucha et al. 2014, p. 2). As ARD was contemporarily understood to be a multifactorial disease, with soil type, edaphon and the endophytic microbiome playing interacting roles, rootstocks may show different levels of symptoms, but no general tolerance could be found, yet (Winkelmann 2025).

Resistance or tolerance to fireblight, woolly apple aphid, crown rot (*Phytophthora* spec.) and apple proliferation can be altered by the type of rootstock, that is used for the apple tree (Dhurve et al. 2023; Fazio et al. 2022; Petruschke 2020).

Rootstocks are differing in their relation to viruses, some of them showing tolerance, others resistances and derived (in)compatibilities with scions, when infections are present. Most cultivars grafted on seedings rootstocks are just as wild species seldomly affected by the ubiquitous tomato ring spot virus and virus diseases in general (Richard P. Marini; Gennaro Fazio 2018; Hanke; Flachowsky 2017).

Altering of the tree's reaction on abiotic factors

Rootstocks are altering the trees ability to take up nutrients from growing media (Richard P. Marini; Gennaro Fazio 2018).

They are also impacting the ability to withstand waterlogging conditions: waterlogging lasting for 4 weeks was affecting scions differently, when grafted on 8 different, dwarfing or semi dwarfing rootstocks from the Geneva (G), Cornell Geneva (CG) and Malling (M) series. Leaf potential, net photosynthetic rate, and stomatal conductance, recovery and eventually trunk cross sectional area and dry weight differed significantly for different rootstocks. (Choi et al. 2020).

Chilling requirement was found to be influenced by the rootstock of grafted scions (Young; Werner 1984) with one experiment with 'Gala' and 'Fuji', allowing to lower their specifically high chilling requirement (Fazio; Robinson 2022; Finetto 2004).

Cold hardiness, frost tolerance and floral bud mortality due to frost events, as well as tolerance to “problematic” soils are goals that can be pursued by breeding and using suitable rootstocks for apples, as these traits are influenced by the rootstock as well (Dhurve et al. 2023; Saini et al. 2025; Richard P. Marini; Gennaro Fazio 2018).

Drought conditions were found to be tackled with distinct strategies by different rootstocks, covering long or short term drought conditions via regulation of transpiration or enforcement of root growth (Tworkoski et al. 2016; Xu; Ediger 2021). Root architecture, vigour, aging, vessel characteristics and ability to be colonized with symbiotic mycorrhizal fungi are impacting the rootstocks ability to absorb water (Richard P. Marini; Gennaro Fazio 2018).

When heat occurs, rootstocks reactions on root zone temperature are differing, by rootstock cultivar (Richard P. Marini; Gennaro Fazio 2018) and rootstocks are not only showing different reactions on heat stress themselves, but also seem to be altering expression of heat stress related genes and heat stress reactions of scions, they are grafted with (Richard P. Marini; Gennaro Fazio 2018).

Roostock's and scion's drought tolerance was also studied regarding the performance in fruit morphology, yields and quality under drought stress, with different combinations producing different outcomes. (Xiaosheng et al. 2024).

Even fruit damage by sunburn was significantly differing between rootstock types, with the most vigorous, large-dwarfing, rootstocks in the experimental set up showing the least yield reduction in an experiment in Canada (Xu et al. 2022).

As chilling temperatures during flower period, as well as heat and drought during pollen germination are critically dangerous for fruit setting and yield, influence of rootstocks on these traits of the scion's inflorescence were investigated – and concluded to be relevant in an experiment with 4 different rootstock types and the cultivar 'Fuji' (Zebro; Heo 2024).

Rootstocks are differing in their ability to tolerate soil salinity levels and different soil pH values, a trait that could also be altered by mycorrhizal interaction (Richard P. Marini; Gennaro Fazio 2018). Rootstocks and their interaction with scions and the environment are having a complex influence on grafting compatibility and likeliness of union breakage. Anchorage of the tree and their likeliness to lean, resulting in probable need of manmade support for a stable stand is influenced by interactions between rootstocks, scions and soil conditions (Richard P. Marini; Gennaro Fazio 2018).

In general, the eventual phenotypic expression is not influenced by rootstock, scion or rootstock x scion interaction, but the outcome of rootstock x scion x environmental interaction (Albacete et al. 2015).

Considering the vast importance for tree fruit cultivars and impact of apple rootstocks, a long and sophisticated history of rootstock breeding is not surprising and will be summarized below.

Breeding of apple rootstocks: historically and contemporarily

The history of apples and apple rootstocks was traced back impressively by Juniper; Mabberley and Mudge et al. (2022; 2009 resp.) and Bartha-Pichler et al. 2005, providing the sources of the following section if not referred to others.

To propagate apples vegetatively, they historically were grafted on any suitable and compatible wild growing apple tree, that could be found in hedges, forests, and other natural places. These rootstocks were seedlings, originating from the chaotic process of wild pollination, sometimes even natural hybridization, and therefore mostly a product of chance, that was then selected. It can be speculated, that a set of empirically gained rules helped to find rootstocks, that would be beneficial or at least suitable for the scion. This practice is still alive in some rural areas. (Juniper; Mabberley 2022). The outcrossing, self-incompatible character of apple plants (Korban 2021) is causing the uniqueness of any seedling rootstock.

Mostly wealthy inhabitants of the roman empire were familiar with dwarfing rootstocks and even Alexander the Great may already have been in contact with dwarfed apple trees. The 15th century gave birth to a name for rootstocks, that were causing a reduced vigour: the term “Paradise” rootstocks was coined, referring to explicitly fine fruit and vegetable gardens, surrounded by walls or fencing (Greek *paradeisos* = walled garden). While it remains unclear, where and when exactly dwarfing “Paradise” rootstocks originated, their existence and popularity in Europe is documented since the middle of the 18th century. Grafting proficiency was already aware of phytosanitary issues associated with rootstocks that were propagated vegetatively, with seedling rootstocks being known as showing less symptoms of virus diseases. Although the underlying reasons had not been discovered yet. It can be suspected, that “Paradise” roostocks were in use and vegetatively propagated for several centuries, accumulating viruses and fungal diseases and thus being in bad health conditions. In the early 20th century, an institute in East Malling, United Kingdom, nowadays known as NIAB[1] (National Institute of Agricultural Botany), launched a multi-year project for characterization and testing of the “Paradise” dwarfing rootstocks. Types that were showing similar characteristics were grouped, forming the different “M”-series. Cell tissue culture and heat treatment allowed to produce M-rootstocks without virus and fungal disease prevalence, resulting in dwarfing rootstocks in better health condition. It is suspected, that about 80 % of apples worldwide are grafted on rootstocks that were somewhen originating from East Malling, UK. Further research and lucky discoveries led to dwarfing rootstocks with aphid resistance at the institute (e.g. 'Northern Spy' and 'Merton 793') (Juniper; Mabberley 2022, pp. 130–132).

[1] https://www.niab.com/

In Germany, cultivating fruit trees had a long tradition, with Keltic tribes already caring for apple trees, when the roman empire invaded. The roman empire had a big influence, introducing sweeter varieties and further aspects of grafting proficiency. Historical laws dated 480 A.D. were shielding fruit orchards from devastation and robbery. Knowledge about fruit trees was also cultivated by monks in medieval monasteries and apples were highly valued in medical treatments and nutrition.
For many centuries, grafting onto seedlings was common practice and recommended to grow standard apple trees (Feuerhahn 2000, pp. 2–3).

In the era of renaissance, colourful, plenty and exotic vegetables and fruit were en vogue and paradise-like gardens were created for well situated families, holding dwarfed and trained apple trees. Settlements and their inhabitants were motivated or even forced by law to plant trees as a valuable food and back up for any crisis of food supply. These trees were grafted on vigorous, robust rootstocks to grow with little maintenance and provided apples for processing, only serving the needs of the belonging settlements or farms. Meadows under the high crowned trees were used for grazing or production of winter fodder for cattle, assembling a *Streuobst* meadow as it is still known today. Also, areas between the scattered fruit trees could be used for arable farming – a land use practice that already looked very similar to modern agroforestry systems Interrupted by the Thirty Year's War, this practice of using standard fruit and often robust apple trees in the landscape was the state of the art. The 18th century brought up alleys as an aesthetic and military useful linear structure. Soon, alleys with fruit trees emerged, combining the comfortable shade of the high crowns with fruit supply (Richard P. Marini; Gennaro Fazio 2018; Juniper; Mabberley 2022; Mudge et al. 2009).

Many trees were traded between the European countries, with France, Netherlands and England supplying other countries. In the early 18th century, digging out *Malus sylvestris* in forests to use them as rootstocks was still very common. While they were robust towards abiotic and biotic stresses, they were reported to be incompatible with some scion cultivars. Using seedlings from scion cultivars was recommended by S. D. L. Henne due to their more suitable habitus and compatibility. Henne was also researching into the diversity of apple progeny and recommending on selection of rootstocks after germination. (Henne 1796).

Seeds for seedlings rootstocks were used from different origins and qualities in this period. Seeds origins could be distinguished in 7 groups:

- Originally wild seeds (origin from wild plants assured)
- Wild seeds (origin from plants not assured; origin from wildered cultivated plants)
- Seeds left over from cider and juice production
- Seeds left over from French cider and juice production – associated with a homogenous habitus
- Scion’s seeds (seeds from different scion cultivars)
- Scion’s seeds from only one, outstanding qualified mother plant (scion cultivar) – starting 1967

Until 1936, triploid cultivars were often recommended as seed donors, but after surveying the variety of different seedlings, only diploid cultivars with favourable traits were recommended for rootstock production. In 1967, merely seedlings originating from cultivars 'Grahams Jubiläumsapfe', 'Bittenfelder' and ‘Antonovka' were still available, while mixed seeds were not traded anymore (Summary by Feuerhahn 2000, p. 3.)

After the long era of self-subsistence in fruit production, the 20th century introduced modern technologies for processing, curing, storage, and shipping. Industrialization of agriculture and horticulture transformed apples into a good, that could be traded, instead of being used for self-supply. The professionalization of growing fruit, market pressure and high labour costs was favouring dwarfing rootstocks to push for efficiency. Dwarfing rootstocks in dense plantings were producing a higher yield per area with smaller costs for maintenance and earlier bearing, for example. Land was cleared from standard fruit trees, to make space and reduce competition for professional fruit growers. In several European countries, political initiatives are documented, that were aiming to “tidy” the landscape and remove the “cluttery” old trees and to let go of fruit production for procession, that could be realized on low input, extensively maintained standard trees, but to instead focus on the production of high value dessert apples and fruit in general. While rootstocks for standard trees were still considered in the advent of professional breeding, they were more or less neglected soon in the proceed of breeding evolution (Bartha-Pichler et al. 2005; Richard P. Marini; Gennaro Fazio 2018; Marini 2024).

This fact becomes even more obvious, when reading statements of issues and justifications of rootstock breeding programmes, evaluation new rootstock cultivars fitness, that have fully abandoned seedlings and vigorous clonal types from their attempts (cf: NC140[2], Baltic fruit rootstock studies[3] for example).

Remarkably, induction of dwarfing through the rootstock is not used to the same extend in different countries related by a strong apple production sector. While China was producing nearly half of the worlds apples in 2019, its ratio of dwarf and close planting was only 12 % - which is very low in comparison to Germany, where ratio was about 90 %. Anyway, research pursuits in China and Japan were also pointing in the direction of more dwarfing and higher density plantings in 2019. (Wang et al. 2019). Also Turkey is an European country, that was realizing the majority of its production utilizing traditional methods(Muder et al. 2022).

Apple seedling rootstocks are still valued for use cases, when highly vigorous trees with good robustness towards biotic and abiotic stressors are needed – with seedlings additionally being mostly free from viruses and viroids (Korban 2021).

The fact, that the three cultivars 'Bittenfelder', 'Grahams Jubiläum' and 'Antonowka' are still recommended to grow standard sized apple trees is reflecting the long temporal research gap in this field. Vigorous rootstocks from vegetative propagation likewise appear absent in breeding programs and are currently of insignificant interest for standard apple tree plantings outside of private garden and urban settings (Brüntjen 2019).

Differing from the general trend towards clonal propagation and induction of dwarfing, one apple rootstock was recently introduced that was both: propagated by seeds and more vigorous:

Some apple species and occasional cultivars are showing the trait of apomictic seed bearing or the ability of self-pollination is suspected – further research is needed in that area. These are of particular interest for breeders, that are valuing a naturally developed tap root architecture, while still wishing for a uniformly growing progeny. It is suspected, that the commonly used seedlings rootstock 'Bittenfelder Sämling' could the product of self-pollination and that other cultivars like that might be existing (personal communication to German and Hungarian pomologists).

[2] https://nimss.org/projects/view/mrp/outline/18883

[3] https://www.researchgate.net/publication/273893671_Baltic_fruit_rootstock_studies_Evaluation_of_apple_Malus_domestica_Borkh_new_rootstocks

The large-dwarfing Malia® rootstock (D2212) is a contemporary example, that was bred by hybridizing *Malus* x *domestica* 'Laxton's Supberb' with *Malus sieboldii*, that was introducing its resistance against apple proliferation in the seed propagated progeny (Markgraf 04.11.2023; Seemüller et al. 2008). Malia ® was undergoing experiments to evaluate its ability to withstand an artificial inoculation with the phytoplasma causing apple proliferation (Frick 2024).

But, while being described as comparably vigorous, a 3-year trial came to the conclusion, that Malia® is not sufficiently vigorous to support standard fruit trees (Herrmann 2025).

Studies concerning vigorous rootstocks are rare and no more examples could be found by structured literature review.

Requirements climate resilient rootstocks for vigorous, standard sized apple trees

Climate change and biodiversity predictions for Germany must be included in future projects while accounting for vast insecurities and regional features (Helmholtz Gesellschaft 19/03/2024), that are inherent to the modelling of the complex climate system of the planet and it's regional implications. The possibility of a collapsing AMOC current (Rahmstorf 2024) is adding a major factor of insecurity, making preparation for antithetic scenarios imperative.

Modern apple breeding is reducing the complexity of improving a whole germplasm with a "divide and conquer" strategy: Objectives of conventional modern apple rootstock breeding are different from those of scion breeding (Hanke; Flachowsky 2017). Traits that are supporting "climate resilience" (Kopeć 2024) of rootstocks and eventually the compound tree, are to be considered, whenever it comes to breeding towards future rootstocks to effectively address future risks (Flachowsky; Töpfer 2021).

Climate resilience in agriculture can be achieved in different ways: deflecting from future scenarios of climate change, Waqar et al. 2024 are categorizing:

- Soil management for climate resilience
- Water conservation and management
- Breeding strategies for climate resilient crops
- Addressing abiotic stress
- Managing biotic stress
- Using climate-smart agriculture technologies
- Acknowledging (various)future perspectives and challenges

„Expanding crop genetic diversity” is mentioned as one out of 4 potential strategies for enhancing crop resilience to climate variability (Waqar et al. 2024, p. 493). This aspect is also clearly highlighted by Bannier 2016 and Ritthaler 24.08.2024 that are sending an urgent call for genetic diversity in fruit crop breeding, referring to scions and rootstock cultivars, respectively.

As far as it can be judged by the author, requirements for climate resilient vigorous apple rootstocks have not been concerned by researchers yet and hence need to be extracted from literature. The suggested combination of

- Objectives of conventional apple rootstock breeding programs
- Traits that supporting propagation propensity
- Traits that are addressing the specifications of standard fruit trees growing practices
- Traits of “climate resilience”

will be presented in detail in the results part.

Genetic resources for vigorous apple rootstocks

Suitable genetic resources are the foundation of breeding attempts (Hanke; Flachowsky 2017). They can be held available in genebanks or allelic diversity of new accessions that haven't found their way into a conservation scheme yet.

Gene banks

Genetic resources for breeding projects can be drawn from existing gene banks. According to Korban 2021, p. 58, they can be maintained either in-situ as whole tree field collections, in-vitro as a source for virus free, clean material or experimental means; seeds can be stored cold, at – 18 °C, dormant buds and shoot tips are cryopreserved.

A gene bank holding apple accessions is present in Germany (Begemann; Vögel 1995), although few (Brüntjen 2019), rootstock cultivars are represented in the German gene bank for fruit cultivars and they are not marked or highlighted.

Many European countries and worldwide have adopted national fruit collections and are on the way towards a data exchange, that is allowing breeders to tap into alle genetic resources, that are available around Europe and globally. (Food and Agriculture Organization of the United Nations 2025; Korban 2021). An outstanding example the apple collection of the Plant Genetic Ressources Unit at Cornell University and majorly assembled by Phil Forsline, in Geneva, NY, USA (Fazio et al. 2008).

Wild diversity and early landraces

It is known, that *Malus* x *domestica* and the native European crab apple, *Malus sylvestris*, are hybridizing in a significant number of cases and have been doing so in Germany and it's neighbouring states for a significantly long period of time already, since *Malus* x *domestica* has been introduced by Romanian settlers (Höltken et al. 2014; Hoffmann 2017). These hybrid plants are of unique genetics and offering a potential genetic resource for breeding.

In Vietnam, *Malus doumeri* is currently collected in a federally funded program to diversify the genetic resources of apple (FISA 24/07/2025) and *Malus sieversii* from Central Asia, as well as it's hybridized progeny is received as an important resource as well (Taskuzhina et al. 2025). *Malus sieversii* is the main progenitor of the domesticated apple, but endangered in it's natural habitat (Tegtmeier et al. 2025). As described in the section above, *Malus sylvestris* has historically been in use as rootstocks, although probably not being perfectly compatible with all *Malus* x *domestica* cultivars. Compatibility is difficult to be estimated, as there seems to be no scientific evidence due to a lack of trials in that regard. Grafting on seedlings of Malus sylvestris or “wild typed”, heritage apples or seedlings of these appears to happen in Austria, but due to the mentioned possibility of hybridizing, no general compatibility of the two species can be suspected from this practice alone (personal communication, A. Wilfling, 2025).

Wiehle; Dahlem 2021 are suggesting wild, cultivated, and wildered accessions from extreme sites in different countries, for example places along the silk road, that have been growing apple cultivars for very long periods of time already, like Pakistan. Ritthaler 24.08.2024 was pointing out “Hungary, Romania, Turkey, Armenia, Caucasus” as potential sources of interest, due to their traditional practices and in parts extreme growing conditions.
Landraces and heritage varieties are pointed out as a valuable source of genes for plant breeding, also for rootstock by Lazaridi et al. 2024.
Unfortunately, in many cases, genetic variability that is actually on-farm and in use is declining, referred to as genetic impoverishment, due to the intensified and wide spread usage of high performance cultivars in modern agriculture and horticulture (Szot et al. 2022) with many of these resources being in urgent need to be conserved, to save them from vanishing (FAO November 2011). This is also true for very old apple varieties and rootstocks of unknown genetic relations, that are increasingly endangered from die-off due to old age, insufficient maintenance, and climate change conditions (Gross et al. 2014; Szot et al. 2022; Bartha-Pichler et al. 2005).

According to the annual issue of the German pomologists association, the repertory of different rootstocks that are suitable to produce vigorous, long-living apple trees, that can be used for *Streuobst* meadows, agroforestry systems or alleys, is too small and there is neither sufficient economic interest, nor research interest invested in breeding programs for vigorous apple rootstocks, whether propagated as seedlings or vegetatively (Becker 2019b; Schuricht 2020).

An assembly, inventory and/or preservation of historical rootstock types and random seedling rootstocks has been called for in recent publications and events of German pomologists. While scion cultivars and rootstock cultivars are represented in the German collection of fruit germplasms and enjoying recognition for their cultural significance and importance as a genetic resource, unique seedling rootstocks without the status of being a cultivar are absent in the collection(Brüntjen 2019; Streuobstwiesenkongress Erfurt 2024; Schulte 2018; Ritthaler 24.08.2024).

Two out of three commonly used cultivars for seedling rootstocks ('Bittenfelder' and 'Grahams Jubiläumsapfel') are on the German red list of endangered crops (Bundesanstalt für Landwirtschaft und Ernährung 2023), with the third commonly used cultivar ('Antonovka') probably being even too rare to be recognized in the listing, as it’s utilization for rootstock production is even lower comparted to the other two cultivars.

Veteran apple trees, that are probably growing on unique rootstocks, as it could be considered as potentially valuable potential genetic resources for climate resilient, vigorous rootstocks, due to the history of apple rootstock breeding. Especially woody plants growing under challenging conditions have been proven by time and nature and may represent a natural preselection of diversity (Denney et al. 2020; Cortés; López-Hernández 2021).

Citizen science in the field of plants and genetic resources

Searching out and assessing veteran apple trees that are growing under challenging conditions could be a considerably big task, both spatially and temporarily. There are several examples for well managed plant related projects, some even specifically addressing plant genetic resources (Ahlawat et al. 2022; Beaubien; Hamann 2011; Fraisl et al. 2022; Bellucci et al. 2021).

Citizen science is defined as “the participation of people in scientific processes who are not institutionally bound in that field of science” (Bonn et al. 2016; Bonn et al. 2022).Citizen science is acknowledged as an important and accepted research approach, with exploring, documenting and collecting data in the topic of environment, ecology, and biology being dominant in its utilization (Follett; Strezov 2015; Fraisl et al. 2022). Citizen science can encompass different types and levels of engagements and could present a way to bridge the gap between research and action when participants are developing to be dedicated supporters and activists to tackle a particular issue(Phillips et al. 2021; Vohland et al. 2021). Pocock et al. 2017 were pointing out, that citizen science projects can range in spectrums from simple to elaborate approaches and mass participation to systematic monitoring (Pocock et al. 2017, p. 7).

Citizen science is offering a range of tools to allow the collective collection of apple rootstock resources therefore appears to be realistic, especially when it comes to participation of advanced citizens like the German association of pomology and associated networks.

Preservation and collection of fruit genetic resources supported by voluntary work

Citizens, that are already playing a vital and critically important role in preserving apples genetic resources are German pomologists. Their contributions are shortly described below:

The maintaining of vigorous fruit trees in Germany and it's neighbouring states is often realized by voluntary engagement. Operating in an economic system, that is solely monetarizing one ecological service of fruit orchards – the fruit production - the efficiency of standard apple tree growing systems is not competitive (Organic Tools GmbH 2020). Collecting, preserving, replanting, documenting, (geo)referencing and propagating, informing the public and keeping old varieties available as scions can be summarized with the terms "in-situ" or "on-farm" preservation of genetic resources (Begemann; Vögel 1995). This service is – in the case of Germany – organized in a nation-wide operating network[4]. Information about cultivars is stored in a freely accessible online database[5]. These services are voluntarily offered by the German association on pomology[6], that is organized on the state and federal state level and often operating in cooperation with environmental associations, groups, regional stakeholders, tree nurseries or (specialised) tree workers, tree wardens, and fruit-based agroforestry farmers.

Several initiatives around fruits and often apples genetic resources where ignited by pomologists, assuring the preservation of this very foundation of future breeding perspectives (Bartha-Pichler et al. 2005; Grill; Keppel 2008). Although rootstocks were not in the main interest of the association for a long period of time, the recent years sparked ambitions and efforts to unlock the potential of old rootstocks as well. This was clearly demonstrated, with roots and rootstocks being discussed in different recent written articles as well as face-to-face and online events[7].

Old varieties and their characteristics often need to be researched from historical sources, that are also maintained and restored voluntarily in the German horticultural archive[8]. Having access to old varieties historical descriptions is very important to revise the accessions of the national collection of fruit genetic resources, that is also carried out by experienced pomologists (Bannier; Schuricht 29.11.2021).

[4] https://obstsortenerhalt.de/
[5] https://www.obstgarten.biz/
[6] https://www.pomologen-verein.de/
[7] For example: presentations: by H. Ritthaler at rootstock conference IBZ Marienthal 2024; Alois Wilfling at conference on *Streuobst* meadows in July 2024, Peter Markgraf at pomologists conference in spring 2025, formation of a task force for fruit tree's roots and rootstocks: https://www.hochstamm-deutschland.de/nachricht/arbeitsgruppen-beim-pomologen-verein-e-v-aufruf-zum-mitmachen-teil-1
[8] https://gartenbaubibliothek.de/

1.3 Justification of research and research goals

Climate change is imposing unprecedented challenges to landscapes and agriculture. Apple is a relevant tree crop in Germany and Europe. Standard, large growing fruit, and apple trees are likely to be part of the solution towards climate resilient landscapes, as parts of habitats providing ecosystem services ranging from food or quality wood to hotspots of biodiversity under extensive cultivation practice. Suitable rootstocks are imperative for the adaption of apple trees to challenging conditions. Breeding effort was focussing on dwarfing rootstocks for the last century, but unique & diverse seedling rootstocks were the formerly common practice. Very old “veteran” apple trees grafted on these could embody potentials for future breeding programs towards climate resilient, vigorous apple rootstocks. It is suggested to explore both, requirements imposed to future climate resilient, vigorous apple rootstocks and potentials of veteran apple trees via literature research, followed by identification of suitable means to assess veteran apple trees, supported by citizen scientists. Consequently, an exemplarily assessment of veteran apples, their coordinates, and relevant associated data as well as augmentation by relevant grid data is suggested. German pomologists and associated fruit tree enthusiasts are envisaged to be involved in a systematic citizen science approach to produce a dataset that is valuable for future projects aiming to develop climate resilient vigorous apple rootstocks.

Research questions:

1. What requirements are imposed on climate resilient rootstocks for vigorous, standard sized apple trees? (literature work)
2. What potentials for future breeding projects could potentially be embodied by veteran apple trees? (literature work)
3. What citizen science tools could be utilized to collect valuable data on veteran fruit trees? (literature work)

Research goals:

1. Development of an assessment protocol for veteran apple trees with potential for climate resilient vigorous apple rootstocks to be used by citizen scientists
2. Conduction of a citizen science project, that aims to collect data on veteran apple trees
3. Data augmentation with relevant grid data, led by tree coordinates
4. Descriptive Data visualization to promote future use of the data set in follow-up-projects

Please note, that the section on methodology and materials is based on insights derived in literature work, that is described in the results part, therefore bringing forward the information in the present document.

2. Methodology and materials

2.1 Literature research

After gaining a general overview via a rough and intuitive literature research using google scholar, physical literature from the library or recommended by associated experts and scientists of that field as well as the annual issue of the German Association on Pomology, that was mainly documented by hand, a cloud of relevant search strings was collected (digital **appendix** 1).

To identify and/ or fill gaps in the so far grown literature and understanding of the topic, a structured literature research was conducted.

Searching engines and databases

A wide range of different search engines and databases were used to find suitable literature. Suitable Databases were found in a database for databases called DBIS[9], which is hosted by the German University of Regensburg. Databases were checked upon their applicability with example search strings and listed in a spreadsheet for structured literature research in case they were perceived to be viable. A descriptive list of databases that were searched can be found in digital **appendix** 2, the belonging excel table in digital **appendix** 3.

Specialized databases were inquired using selected search strings only and only during the phase of structured literature research. Less specialized databases and search engines were inquired frequently throughout the project.

[9] https://dbis.uni-regensburg.de/

Search engines and databases that were used most frequently were:

Table 1: Search engines and databases used for this study

Name	Details	Access	Reason / Usage
Google Scholar	Bibliographic database, owned by google	https://scholar.google.com/	Wide operating search engine
Core	Repository for open access publications, based at the Open University in the UK	https://core.ac.uk/	If no open access / no license
Wayback Machine	Digital archive of the world wide web, owned by Internet Archive, a nonprofit digital library	web.archive.org	If no open access / no license
Science Direct	"A free to use online platform and database, offering a plurality of functions and opportunities to its more than 1 Million users (students, professors, scientists)."- DBIS	https://www.sciencedirect.com/	Browsing open access Journal section
Researchgate	"Have access to electronic journals and ebooks from the publisher "Elsevier". Access is dependent on the licence your university is holding." - DBIS	https://www.researchgate.net/	Valuable Recommendations
Academia	"Academia is a commercial platform for sharing academic research that is uploaded and distributed by researchers from around the world." – Wikipedia	https://www.academia.edu/	Valuable mail service for papers of interest
Te Kete Wanaka	Lincoln University New Zealand library Search	https://ltl.lincoln.ac.nz/	Well assorted library

Literature management

Literature management was conducted with Citavi, a commercial management tool for literature import, management, work, and citation.

Physical and digital literature information was stored and labelled in Citavi. The function of categorizing was used to allow a structured incorporation of literature, assuring that every title that was found to be useful would be considered. Imported titles were also read, highlighted, and commented in Citavi to prepare for the writing process and to have the key information of the resource on hand.

The Citavi Add-on for Office Word was used to import literature citations into the thesis and automatically create the list of references in the chosen style of citation.

2.2 Designing the citizen science project

Project layout: Identifying the level of participation and general layout

As retrieved from literature work presented in the results section:

- After considering all relevant factors, a citizen science approach is considered **appropriate** to elaborate the research questions and goals.
- The **level of participation** should lay between “crowd intelligence” and “participatory science” due to the autonomous selection and complex assessment of the veteran trees. The project was of a contributive type, with participants mainly contributing data in a preformulated way, but collaboration being aspired to improve the present project and even more to involve participants in follow-up projects.
- To assure quality and avoid overextension, **advanced participants** were defined as the targeted group in recruiting. Referring to the constant engagement and experience of German pomologists and associated groups like fruit tree wardens, they were expected to be especially suitable to engage.
- To manage the data collection, an **assessment protocol** querying traits of interest of veteran apple trees and their rootstocks was developed and provided.
- The collection was fostered to be “**trait specific**” to assure the accessions to be as appropriate as possible for future research and breeding programs. Criteria to choose trees were communicated to be “old age” (≥ 95 years) > “challenging growing conditions” > “vitality”.
- The characteristics of veteran trees and the boundary conditions of the present project are limiting the practicable inputs of citizen scientists to **observations and data collection**.

The rough layout of the present citizen science project:

1. Build knowledge
2. Recruit suitable citizen scientists
3. Develop the assessment protocol for veteran apple trees (rootstocks) that are likely to harbour genetic resources that are meeting requirements of climate resilience
    a. Qualification & background of assessing person
    b. Tree characteristics
    c. Growing conditions
    d. Traits linked to climate resilience
    e. Exact location
    f. Contact details for further/future inquiries
4. Host several online workshops to provide context for (potential) participants, engage participants and give room for questions and networking, facilitating participation of sort "crowd intelligence"
5. Launch assessment protocol and manage data collection
6. Cultivate an open feedback culture to allow improvement and management
7. Review, augment and describe the data

-----------thesis submission---

8. Present data to the participants and other persons of interest
9. Collect feedback
10. Make data available in a database

This layout was integrated into a framework retrieved form literature and will be described in depth in the following sections. Based on what was retrieved from literature and presented in the results section, the project's layout was integrated into a suitable framework. A similar **table** covering the level of participation and coverage of the projects proceeding within this thesis can be found in the results part. The individual steps are described throughout the methodology and materials section

Table 2: Framework of the study

Timeframe	Stage	Steps of the present project
12/2024-01/2025	1: Identifying the problem & research questions 2: Determining if citizen science is the right approach	1: Structured literature research building knowledge
2/2025	3: Designing the project	2: project layout 3: Designing & testing assessment protocol
4/2025	4: Building the community	4: Building contact with potential multipliers & realizing recruitment stategy 5: runing (online-)workshops
5/2025 –	5: Managing the data (= planning, collecting, assuring, analysing, describing, and preserving, integrating)	6: Launching and manging of assessment protocol 7: data reviewing & structuring 8: data augmentation & description
5/2025 –	6: Evaluating the project	9: Evaluation and feedback form

Bureaucracy and organization

Finances

Financial support for the present project was low but covered by the partner of the thesis (BaumLand-Kampagne[10]). Expense allowance or material incentives for citizen scientists were therefore excluded from further considerations. No external funds were raised.

Legal issues

The main source to review legal issues touching upon the present project was a guidebook provided by Museum für Naturkunde 2020.

[10] https://baumland-kampagne.de/

Insurance coverage

Citizen scientists are covered by their personal health insurance, when fulfilling tasks for a citizen science project. In case of somebody else or something else being accidently and not recklessly injured or damaged while fulfilling the tasks, the participants third-party insurance is liable, if existing. If the participant does not hold a third-party-insurance, the belonging federal state's insurance covers the case if it was directly linked to the voluntary mission of the citizen science project.

Participants were informed about their insurance coverage via a document on legal issues they received via mail, once registered in the project and asked to behave conscious and within the given law. Only information considering German law could be provided. Participants from other countries were asked to make sure they were informed about the situation in their place.

The document on legal issues was placed at the start of the assessment protocol followed by the mandatory prompt to leave a signature to state the knowledge of this very important information.

Data protection

The data privacy statement included:

- **Intention of the research project** for transparency reasons and to be referred to when personal data is used only to serve the intention of the research project. Also including a statement on principle values chained to the project. It was referred to these values when potential data transfer was described.
- **Statement on private data uses,** including defined use cases, time frames for data usage and storage as well as rights of participants.
- **Information on „*jotform*",** the software tool to enter and upload data, specifically about cookie policies of "*jotform*".
- **Provisions to provide data safety,** including limiting persons that are handling personal data and having access to it.
- **Provisions to provide misuse of data on veteran trees**, describing the gatekeepers function of the person that is named as the contact person in the assessment protocol. This part was mainly included due to persons visiting the online workshop or writing emails, expressing concerns, that the genetic resources of "their" trees could be monetarized by commercial enterprises.
- **Example for a realistic follow-up project**, that could make use of the data collected in the present project. Described was the inclusion of the dataset into a database.

The document on data privacy and insurance coverage can be read in digital **appendix** 4.
For transparency reasons, the key facts of legal issues were also part of the online workshops, that all registered persons were invited to several times.

Goals of the citizen science approach: Addressing needs of researcher and participants
The citizen science project was aiming for integration of five subgoals focussing on the citizen science element of the present thesis (based on Fraisl et al. 2022; Soßdorf et al. 2024):

- **Goal 1**: Data collection for fulfilling the research goal: assessment of veteran apple trees with potential for climate resilient vigorous apple rootstocks
- **Goal 2:** Addressing the needs of participants (for example: relevance of the issue, possibilities to contribute values, learning as gaining expertise or knowledge, being part of an active community, data safety and ease of application (Soßdorf et al. 2024, p. 27))
- **Goal 3**: Assuring data quality
- **Goal 4:** Assuring future data usability
- **Goal 5:** Fostering improvement via feedback and evaluation

Although attending a workshop and eventually assessing a tree was the main goal of the project, communication was also highlighting opportunities for interested persons to learn and get to know others for networking reasons. According to Soßdorf et al. 2024, this emphasis on the symbiotic relationship is important to motivate potential participants to show up and stay interested and engaged.

The consideration of the goals will be described separately for the assessment protocol.

Elements of the project that addressed the goals beyond the assessment protocol are briefly described below:

Addressing the needs researcher and participants

Alongside to others throughout the citizen science project, the following elements were integrated in *assessment protocol*, addressing the 5 goals of the citizen science project mentioned above:

- To **facilitate the search and selection of suitable trees**, two different supportive materials were created. These materials were serving the needs of participants, by preparing them for their task, but also assuring data quality.
    - A slide **explaining the criteria** ("old age" (≥ 95 years) > "challenging growing conditions" > "vitality", cf. results section.) to select a tree for an assessment and describing the options and obstacles of estimating the age of a veteran apple tree. The latter was mainly assuring participants, that there was, unfortunately, no non-invasive and precise methodology they could apply, but that reports of local witnesses of the past, the context of the growing site, probably archived information on planting dates or dates of creation of the whole setting and – as the least reliable option – the experience of well - trained pomologists and tree wardens could help with estimating, whether or not the tree was sufficiently old (**appendix** 5). One additional indication for old age was provided with the second supportive material:
    - **A list of online links for aerial views**, few of them reaching back as far as the 1930s. When trying to estimate the age of a tree, participants had the chance to check, if the tree was visible on these photos, already. Unfortunately, not all federal states were offering aerial views for free.
      The list can be found in **appendix** 6.
- Two questions were representing **strict criteria** of the data collection: One asking for the estimated decade of planting and one asking, if the tree could possibly be a crab apple (*Malus sylvestris*). When stating, that the tree was probably planted later than 1930 or that it was likely to be a wild apple, the whole protocol collapsed and informed about the fact, that accessions of these types were not the focus of the project and should not be assessed. This way, data quality was assured.

- **Division of the protocol** in one informative and 7 interactive blocks, alongside with brief introductions, not only allowed structuring for orientation (Methodenportal der Uni Leipzig 11/09/2025), but also provided the opportunity for saving the protocol for later after each block, a function of the *jotform* form builder. Order of the blocks and questions was trying to cluster questions of similar type. At the same time, cumulating comparably complex questions in one section was avoided as good as possible, both aiming to make the processing easy on the participants concentration.
- A set of questions specifically aimed to **estimate the quality of each data set**: What was their expertise in observing and assessing old apple trees? Did they attend an online workshop that was offered in the course of the project? What foundation did they estimate the apple tree's age on? It was objected, that these questions could be used to evaluate the quality and reliability of the dataset, when prioritizing candidates for potential follow-up projects – a mean of data quality assurance.
- Photo in block 2/7: A **photo of the tree** could prove useful to recognize it in case future surveying or sampling should take place, supporting future usability of the data. Anyway, the photo widget was also implemented, as several participants or potential participants sent photos prior to the data collection phase and reported of the impressing characteristics of "their" trees. Hence, it was assumed, that sharing photos could be rewarding for participants. Also, photos are a very good token to represent the data collection, that is realized by the participants and that could be used in a final online meeting or lateron in presentations to celebrate what the volunteers were able to achieve.
- **Coordinates** were the important anchor to allow data augmentation with grid data and that could allow further augmentation in follow-up projects to identify the most interesting candidates for surveying or sampling. Coordinates thereby helped to improve data quality independent of citizen scientist's skills and to assure future usability of every single data set.
- **Supportive material** was provided to handle difficult questions, level out different levels of expertise and thereby assure data quality. Gaining expertise or training their skills with these slightly more difficult questions is another benefit, serving the needs of the participants. This way, they had the opportunity to learn about:
    - Apple phenology and BBCH coding
    - Soil sampling and determining soil types
    - Indicator plants for phenological seasons and soil conditions
    - Standardized measurements of trees
    - Differentiation of domesticated and wild crab apple

- **Auxiliary questions** appeared, when an information was needed to interpret another, to assure the actual questions quality (e.g. sampling position of leaves, scion cultivar to relate rootstock's behaviour to scion's characteristics).
- The question prompting to state whether the tree was grafted and if so, in what position(s) it was grafted, was one out of a few important questions to allow "**filtering"** or **conditional formatting**, meaning, that some questions would be automatically excluded if triggered by predefined inputs. Filtering is a common method to make questionnaires less complicated for participants, to assure that input data is not contradictory and to shorten the procedure if possible (Methodenportal der Uni Leipzig 11/09/2025).
- Several **free text fields** were provided whenever multiple-choice questions were likely to oversee important features of a complex issues in border cases, or otherwise, many questions would be needed, which would be irrelevant for most participants and thus inflate the protocol (e.g. diseases, local growing conditions). Input of these fields is difficult to be analysed, but could in some cases prevent misleading data interpretation, thereby assuring data quality. On the other hand, the general style of the protocol were **multiple or single choice questions** to allow easy data analysis and assure quality by standardizing inputs.
- Questions and answers were designed in an easy language, a repetitive manner, not suggestive, univocally, explicit and without technical terms as far as possible, thereby avoiding miscommunication and assuring quality as well as ease of use for the participants (Methodenportal der Uni Leipzig 11/09/2025).
- Questions about suckering and reproduction of suckering rootstocks were included to inform potential follow-up projects about **options for propagation**, in case they are interested in propagating the veteran tree. A suckering tree is easily propagated via cuttings, for example. Thereby, these questions served future usability.
- Making some crucially important questions **mandatory** was assuring, that only complete datasets would be handed in – serving the data quality and future usability. Whenever these mandatory questions were linked to a substantial effort, like measuring, sampling leaves, for example, the option "I will answer this question later on" was provided, to give participants **control over their workflow**. But: The protocol couldn't be submitted with any "I will answer this questions later on" in place, reminding participants to answer every mandatory question.
- Always providing the **options "I don't know" or "I can't judge"** when a question was mandatory, is important to not force participants to guess or put in random answers– serving the data reliability and quality.

- To **adjust questions for the level of expertise of participants**, relatively difficult questions were repeated, for example: when questions on phenology were perceived as too complex and answered with “I can’t judge”, an alternative question, the relative development in comparison to other local apple trees, was prompted. Some voluntary questions explicitly addressed persons of high expertise and asked for their opinion on complex issues, that needed the integration of information and a resulting conclusion. Thus, allowing to always collect the most accurate data on the issue.
- The **nomination of a contact person** for each tree addresses the need of participants to keep control over the potential genetic resources they are assessing, and facilitates future usability, when enabling access and sharing valuable information.
- **Data protection** is an imperative element of a citizen science project, addressing not only the needs, but the rights of participants. Data protection and control over the data participants are contributing was actively demanded by some participants when attending the introduction online workshops. The signature of consent with the data protection statement that was set to be mandatory to proceed with the assessment protocol is an important agreement, addressing the needs of the researchers to use data, and of participants, to have their rights respected.
- To address the variable technical equipment and skillset of participants, not only the online form, but also a **PDF version of the assessment protocol** and recommendations for an assessment without the support of a smartphone were handed out. This included, that alongside recommending several apps to determine cardinal directions or botanize plants for example, also suitable literature, to take a compass to the location or to have a map handy to mark the correct position of the tree, was pointed out.

Designing and testing of assessment protocol

The overall layout of the protocol was divided into eight blocks:

1. Preliminary information
2. Basic data of the assessment
3. Basic data of the tree
4. Description of the growing location
5. Description of tree vitality
6. Description of leaf characteristics
7. Influence of climatic conditions
8. Accessibility of the tree and contact person

Table 3: Main body of the assessment protocol

A pdf version of the protocol can be found in digital **appendix** 7.

	Main Goal	**trait of interest/ reasoning**	**Questions / description of assessment protocol**
Preliminary information			
/	Addressing the needs of participants; assuring data quality; fostering improvement	Informing participants about project goals to build motivation, excluding trees or volunteers that are not appropriate, supporting suitable preparation to manage the task of the assessment, avoiding frustration by technical issues, providing data safety, assuring future data usability by signed statement of agreement, communicating open feedback culture to allow fast management of issues	What the assessment is about
			What should be considered before starting with an assessment, e.g. what equipment is recommended and technical details on the assessment tool
			Photo and contact details of the project management, invitation to give feedback and report any issues
			Document on legal issues and prompt to verify the participants agreement with a signature
Question Nr.	**1/7: Basic data of the assessment:**		
1	Fostering improvement	To track assessments over project span and evaluate over time frame	Date of the assessment
2	Fostering improvement, Assuring data quality	To identify spatial gaps for future projects, additional to tree coordinates to use imprecise place for public presentations	Place of the assessment
3	Assuring data quality	For follow-up questions regarding data	Name and contact details of the assessing person
4	Fostering improvement	To gain information about the participants to refine potential future target-specific recruitment	Interests of the assessing person
5	Assuring data quality	To contextualize each data set and allow to prioritize, when it comes to selection of candidates	Experience of the assessing person
6	Assuring data quality	Similar to experience	Attendance of an online workshop
	2/7: Basic data on the tree:		
7	Assuring quality	Foundations are of different reliability	Foundation of age estimation (options were e.g. “local knowledge” or “estimated by own experience”)
8	Data collection	age	Estimated age
9	Assuring future data usability, addressing the needs of participants	Easing retrieval, meeting participants interest in sharing photos of trees	Photo of the tree
10	Data collection, addressing the needs of participants	phenology, phenological adaption	Current phenological state (BBCH code, supported by a pdf explaining the codes with pictures)
11	Assuring data quality	Phenology; phenological adaption	Development in relation to other trees
12	Data collection, Addressing the needs of participants	Vigour, height	Estimation of tree height (supported by a pdf explaining and depicting the estimation utilizing the intercept theorem)
13	Data collection	Vigour	Estimation of crown diameter (supported by a pdf explaining and depicting the estimation)
14	Data collection	Vigour	Length of the stem
15	Data collection, addressing the needs of participants	Vigour, stem circumference	Circumference of the trunk (supported by a pdf depicting the height of the measurement for different cases)

16	Assuring data quality	Auxiliary question, triggered by conditional formatting	Grafting, grafting position (including multiple grafting)
17	Data collection	Vigour	Comparison of scion and rootstock vigour
18	Data collection	Propagation	Presence of root suckers
19	Data collection	Propagation	Blooming or fruiting of root suckers
20	Assuring data quality	(Not a crab apple)	Option to state, if the tree is likely to be a crab apple (*Malus sylvestris*) (supported by a pdf showing characteristics for differentiation)
21	Assuring data quality	Auxiliary question	Scion cultivar
	3/7: Description of the growing location:		
22	Data collection, assuring future data usability: for data augmentation	(Challenging) growing conditions	Coordinates
23	Data collection	Phenology/ phenological adaption	Phenological season (supported by a list of indicator-plants for the phenological seasons)
24	Data collection	Heat and sun tolerance; drought tolerance	Sun exposure/shade by cardinal directions
25	Data collection	(Challenging) growing conditions; late frost tolerance, frost tolerance; drought tolerance	General exposure
26	Data collection	challenging local conditions	Topography within a 5 m radius
27	Data collection	Challenging growing conditions	Soil type (supported by a pdf explaining and depicting a simple procedure to determine soil types)
28	Data collection	Challenging growing conditions	Parent material/ bedrock
29	Data collection	Salt tolerance, pH tolerance, challenging growing conditions (soil)	Soil characteristics by indicator plants (supported by a list of indicator plants for different soil conditions)
30	Data collection	Drought tolerance	Local conditions favouring drought stress? (Integration of local conditions and estimation prompted)
31	Data collection	Waterlogging tolerance	Local conditions favouring waterlogging stress? (Integration of local conditions and estimation prompted)
32	Assuring data quality	Covering what can’t be covered by standardized questions	Other important features of the growing location
	4/7: Description of tree vitality		
33	Data collection	Vitality	Vigour of annual shoots
34	Data collection	Vitality	Branching in periphery of the crown
34	Data collection	Vitality under given maintenance condition	Maintenance condition: estimated last pruning
35	Data collection	Tolerance/ low sensitivity for fungal diseases, resistance	Fungal diseases
36	Data collection; assuring data quality; addressing the needs of participants	Tolerance/ low sensitivity for diseases, resistance	other diseases or abiotic damages
	5/7: Description of leaf characteristics		
37	Assuring data quality	Auxiliary question	sampling position in the crown
38	Data collection	Leaf size	leaf size
39	Data collection	Leaf trichomes	presence of leaf trichomes
40	Data collection	Leaf cuticle	strength of cuticle
41	Data collection	Leaf thickness	leaf thickness
	6/7: Influence of climatic conditions		

42	Data collection	challenging growing conditions (historically and contemporarily)	extreme weather events of the past
43	Data collection	challenging growing conditions (historically and contemporarily	extreme weather conditions during the past 2 -3 years
44	Assuring data quality	Auxiliary question	relative blooming time
45	Data collection	phenological adaption to extended vegetation period: Late frost tolerance	damages caused by late frost events
46	Data collection	phenological adaption to extended vegetation period: normal leaf senescence	leaf senescence
47	Data collection	General climate resilience	Overall damage by recent climate change conditions (integration of local conditions and estimation prompted)
	7/7: Accessibility of the tree and contact person: context of the tree, ease of access, naming of contact person, final remarks)		
48	Assuring future data usability	To inform conductors of potential future studies about sensitive settings	Setting of the tree (e.g. private garden, park, etc.)
49	Assuring future data usability		Accessibility
50	Assuring future data usability	To link a contact person to every data set to pursue future accessibility, to have a "gate keeper" that can decide, if the tree and its data can be used for specific projects	contact person
51	Assuring future data usability	To simplify the next step of making data available	consent for data transfer in a database
52	Assuring data quality; Addressing the needs of participants	To allow participants to write down what they feel like is important information not yet covered	final remarks

Evidently, when comparing to the traits of interest listed for veteran apple trees in the results section, a range of traits of interest is not part of the assessment protocol. These missing traits were either not suitable to be observed and assessed by the recruited citizen scientists or prioritized lower than the traits that were included in the protocol. Emphasis was put on the coverage of the most important clusters of traits that were roughly represented by the blocks: tree vigour, local growing conditions, vitality, a selection of leaf characteristics, and exposure to challenging climatic conditions.

Set up in *jotform* form builder

The form was set up in the online form builder *jotform*. Widget for example for questions, pdf presentations, pictures, saving and proceeding buttons can be added by drag and drop.

The number of applications and use of the online signature service to document the participants agreement with the data security statement was requiring a low-level paid plan of the service ("Bronce level").

Using the widget to map locations of the tree required the creation of a google maps API key via the google dashboard, due to the frequent use of google services. The minor utilization of the service was covered by free usage conditions.

Pretesting

The assessment protocol was checked by different persons several times, before being used to assess some, still exemplarily trees in the field. Including the creator of the protocol herself, 5 persons of different expertise in the field tried the protocol, provided feedback, and enabled improvement prior to the official launch. The hardcopy version was tested once, and its final form was oriented at the final online form. Data of these exemplary trees was deleted eventually. Alongside with fixes of the conditional formatting, the pretest revealed, that the online form was malfunctioning when network coverage was bad. As coverage is not granted in all places and veteran trees could also grow very remote, the PDF protocol was also a valuable option if the network connection didn’t support the online form’s functions.

2.3 Building the citizen science community

Recruiting strategy

According to Soßdorf et al. 2024, an appropriate recruiting strategy is important to reach those potential participants that are actually benefiting from participation and engaging with motivation – the obligation of a successful citizen science project.

Elements of a recruiting strategy are:

- **definition of a target group** of potential participants, to allow an adapted advertisement, means of communication and the next step: a definition of the roles and tasks, they could be engaged with.
- definition of **suitable roles and tasks for potential participants**, to address persons whose resources are matching the requirements and to avoid miscommunication
- **Identification of potential multipliers, supporters, and mediators**, that are facilitating the communication from researchers to potential participants

These elements will be filled with their realization in the present project, below:

Target group

As literature research had recommended to include the level of expertise in the definition, and the protocol’s questions were partly challenging, the target group was defined to be of advanced experience. Accordingly, the mean age was expected to be comparably high, as it takes time to build experience.

Oriented on personal experience built on respective events, exchanging with other experts in the field and backed up by the literature mapping today’s role and relevance of vigorous apple trees, the following target groups were defined:

Major relevance:

- **Practitioners**, Practical use/agroforestry and tree wardens: Everyone that is actively and probably commercially working with vigorous apple trees
- **Environmentalists:** People mainly interested in nature preservation with vigorous apple trees, e.g. as a part of *Streuobst* meadows
- **Pomologists,** that couldn’t be assorted to just one of the groups above, but that had been identified as an important target group in the introduction

Minor relevance:

- **Researchers** active in the field
  (less relevant mainly due to small cohort)
- **Hobby** – Persons that are interested but not prepared with relevant experience
  (less relevant due to little experience)

Suitable roles and tasks for potential participants

Oriented at the level of participation mentioned in the general project layout, tasks for participants were communicated as:

- “Collecting veteran apple trees, utilizing a standardized methodology for the assessment”
- They would be informed in a workshop
- They would have the chance to get in touch with other participants from other places

The workshops were offering a chance for the researcher to reality check the assessment protocol and improve it with feedback, which participants were encouraged to give to adjust the tasks they would fulfil.

Identification of potential multipliers, supporters, and mediators

Via online research and exchange with experts employed at the cooperation partner, a list of potential multipliers was created, which can be found in digital **appendix** 8. Federal state and country of the multiplier was noted, as well as the most applicable target group and an email address.

The list encircled associations, enterprises, single persons of wide influence in their network, professional associations, researchers, magazines and suitable group channels on the messenger telegram and Signal, that other employees of the cooperation partner were already part of. Employees of the cooperation partner were also appealed to spread the word and advertising material at events they would visit within the time frame of recruiting. Social media advertising was not considered to be viable, as the cooperation partner didn’t use social media at that point and the setup of an explicit social media strategy was going beyond the limited resources of the present project.

Producing advertising material

Integrating the defined target groups and roles for participants, advertising material was created. The two target groups with major importance were recognized: practitioners and environmentalists, to create two different versions of posters and flyers, that can be found in **appendix** 9.

Alongside, the following materials for advertising were created, without focussing on one of the target groups:

- Standard email(s) to inform multipliers and appeal them to forward and spread the call for participation. This standard mail included a colourful banner and was accompanied by flyers, posters, a sharepic formatted for Instagram and a square shaped sharepic.
- A sharepic, meaning a small, square shaped picture with the key information, that could be used for advertising in group channels in messenger groups and be forwarded to multipliers
- A text for the website of the cooperation partner
- A **press release** that was handed out to registered persons to enable them to spread advertisement via local newspapers and motivate local communities to report veteran tees to assessing persons

All the materials mentioned are accessible in digital **appendix** 9.

Advertising for project registration

The main focus of the advertising material was to convince potential participants to access a short online form, that was:

1. Providing background information on the issue, describing its relevance
2. Describing the steps of the present project: After registration, invitations for online workshops could be expected, followed by the data collection phase and eventually a closing meeting, when achievements could be celebrated and outcome of data analysis would be described to the participants
3. Communicating the target group of the project, to avoid many registrations of persons with insufficient experience
4. Appealing interested persons to leave their email address to be informed and invited for upcoming workshops and other issues throughout the project

A pdf export of the *jotform* registration form is accessible in **appendix** 10.

Every person registered in the project was welcomed via email and provided with the most up to date information. This welcoming email was adapted throughout the project, initially containing basic information, dates and times of upcoming workshops, later stating that the phase of workshops had passed and assessments were running, referring to a record of the online workshop and including all supportive material for tree selection and multiplying advertisement. Eventually, the welcoming mail stated that the researchers were pleased about the persons interest, but the phase of data collection was over and inviting for the closing online meeting and stay in touch.

Incentives

Incentives are an important part of an effective recruiting strategy (Soßdorf et al. 2024). Though material incentives could not be realized in the present project due to financial restrictions, meeting the anticipated needs and interests of potential participants were communicated as incentives, e.g. “exchange with others” and collaborative achievement of a shared goal as well as learning the structured assessment of apple trees and thereby growing their own knowledge.

Communication

Communication with participants was mainly realized through the email addresses, they had put in the registration form to express their interest. Personalized mass mailing was utilized to approach participants more personally.

As some persons had provided their phone number as well, these were called when a long lag phase of assessments triggered the researcher to enquire the reasons and encourage participants to assess trees. As some persons attending the online workshops had expressed that communication via a signal group could be an easy and accessible way, a signal group was set up as well and equipped with the same information that was sent via email. This is, where exchange between participants could take place without involving the project management.

Introduction workshops

The introduction online workshop was repeated six times from late March 2025 until late May 2025. It included:

1. Introduction to important Zoom functions to participate
2. Overview
3. Introduction of researcher and participants structured by questions, with an option to accelerate if too many attendees were present
4. Information about the cooperation partner and the motivation for the present project as well as potential future perspectives
5. Different steps of the present project, beginning with the workshop and finishing with the closing online meeting at the end of the year
6. Information on how to find and select veteran trees: Naming the criteria: “old age” (≥ 95 years) > “challenging growing conditions” > “vitality”
7. Information on the assessment protocol and a run through the tool to show the different sections
8. Information on data security
9. Room for questions and remarks, reminder to always get in touch when questions appear
10. Opinion poll on how to enable exchange throughout the project and potentially beyond (for example: mail chain, group chat in a data safe messenger)
11. Thanks to all participants and goodbye

Describing the assessment and skipping through the assessment protocol, mentioning important skills, preparation, materials and time that would be needed to complete an assessment. This overview was meant to help participants to decide, whether the task would be doable for them. At this point, guests of the workshop were encouraged to point out any obstacles they could see and wanted to talk about – to create a positive feedback culture and allow final improvements of the assessment protocol.

Sharing relevant knowledge and establishing a personal connection to the researcher was meant to support the “crowd intelligence” type of participation.

Communicating a positive relation to feedback during the online workshops aimed to yield important hints to improve the project.

The presentation sheets of the online workshop are accessible in digital **appendix** 11.
A record of the workshop is accessible part of the digital **appendix** 12.

The workshop was carried out personally in the field once, at the annual spring conference of the German Association on Pomology in early May in Naumburg. Participants of the workshop could try the protocol to exemplarily assess trees on an apple meadow nearby.

Closing online meeting

The closing meeting is taking place later than the submission of this thesis. Participants were invited to join one out of two identical meetings. The agenda is encircling:

1. Welcoming everyone
2. Brief summary of what happened in the project
3. Slideshow with veteran trees assessed in the project to celebrate the achievement
4. Presentation of interesting data analysis
5. Input from a member of the German Association on Pomology on the possibilities of storing the data safely in a searchable database
6. Input from a member of the taskforce for rootstocks within the German Association on Pomology about other activities in the field
7. Input from a Baumland employee on a follow-up project that is planed and in preparation
8. Open end with room for discussion and to find out
    - what follow up projects could look like and how one could get involved
    - feedback for the project to allow improvement

2.4 Managing the data

Data reviewing & structuring

Measures to improve data quality and future usability were already mentioned in the section concerning the projects design.

Assessment tool and initial data storage were set up in the *jotform*[11] form builder, a browser-based tool for online forms. Forms are set up via drag and drop of a wide variety of "widgets" and can be customized easily by the researcher. Automatized emails are included to keep participants and the researcher informed regarding the status of the data collection or data upload.

When assessing a tree, data was stored on a European based server of the form builder. *Jotform* is assuring GDPR (General Data Protection Regulation of the European Union) compliance and offers the option to store data on European servers only.[12]

Data reviewing & structuring

Datasets could be exported from *jotform* in a **table** in .xls-format, with each question constituting a column header.

In Excel, data was checked regarding missing values. As questions had been ordered to be convenient for participants, the data was resorted. Unfortunately, the *jotform* output was giving back answers on multiple choice questions in one cell without delimiters, making it necessary to use "IF" and "TEXTSPLIT" functions of Excel or even sort values by hand to be most time efficient.

Participants inputs and choices were renamed just as columns to suit the need of data analysis. As the questions of the assessment protocol had been structured to meet the participants needs, data needed to be structured by categories of similar topic to provide a suitable overview for exploration. An overview is provided in **table** 6 below. Categorizing was allowing to choose data for further exploration, resulting in various figures to eventually provide a wide overview.
Eventually, data for descriptive analysis was selected. Although different parts of the data would have been worth shown, a preferably diverse selection of tree and growing site characteristics was chosen, completed by data on the initially registered persons and those that had actually contributed trees.

[11] https://eu.*jotform*.com/de/
[12] For information on GDPR compliance and storage on European servers visit: https://www.*jotform*.com/help/871-how-to-store-your-data-on-eu-servers/

Once being downloaded from a *jotform* server, data was stored on a Nextcloud server provided by the cooperation partner in a separate folder. Personal data and topical data was indexed and split to depersonalize the data for analysis.

The original data set, restructured data and data sets for import in statistical software are accessible in the digital **appendix** 13. Personal data of the participants are not included due to personal data safety reasons.

Data augmentation and descriptive analysis

Data processing included:

- Grouping the raw data by the following categories and choosing at least one aspect of each category to be involved in a **figure**, plotting figures to explore the data (**table** 4)
- Geocoding home counties of registered persons, utilizing the R package “tidygeocoder” and Open Street Map interface
- Extracting altitude data for every tree’s coordinates utilizing the R packages “ncdf4”, “raster”
- Extracting water retention index for every tree’s coordinates, utilizing the R package “raster”
- Extracting daily precipitation sum for every tree’s coordinates, utilizing the R packages “ncdf4”, “raster”
    - Summarizing daily precipitation by grouping and summarizing with R packages “dplyr” functions to get annual mean rainfall for each side
- Plotting of registered persons and assessed trees on maps, utilizing the R package “rnaturalearth” and “rnaturalearthdata” to add polygones of administrative borders for better orientation.

Table 4: Categories of raw data

Category	Description	Data/ data shown in figures	Figure
“quality”	Indicating the whole datasets quality	Workshop participation	5
		Experience	
		Foundation of age estimation	
		Tree age	
“vigour”	Describing the trees vigour	Length of the stem	10
		Estimation of tree height	
		Estimation of crown diameter	
		Circumference of the trunk	
		Comparison of scion and rootstock vigour	
“vitality”	Describing the trees vitality	Vigour of annual shoots	8
		Branching in periphery of the crown	
		Maintenance condition	
		Fungal diseases	
		Overall damage by climate change conditions	
“usage”,	Data indicating future propagation and survey opportunities	Presence of root suckers	12
		Grafting, grafting position	
		Blooming or fruiting of root suckers	
		Additional information on surveys concerning the tree (e.g. genotyping)	
“phenology”	Data describing the trees phenological reaction	Date of the assessment	6, 7
		Current phenological state (BBCH)	
		Development in relation to other local trees	
		Phenological season	
		relative blooming time	
		damages caused by late frost events	
		leaf senescence	
		Scion cultivar	
“adaption”	Data describing the trees potential adaption to challenging conditions	extreme weather events of the past	9, 11
		leaf size	
		presence of leaf trichomes	
		strength of cuticle	
		leaf thickness	
“conditions”	Data describing current growing conditions	Sun exposure/ shade	7,9,8
		General exposure	
		Topography in the locally 5 m	
		Soil type	
		Parent material/bedrock	
		Soil characteristics by indicator plants	
		Local conditions favouring waterlogging	
		Local conditions favouring drought stress	
		extreme weather conditions during the past 2 -3 years	
Grid data	Data added by coordinates	Altitude	5, 8, 9, 10
		Precipitation	
		Water retention index	

Sun exposure was queried for cardinal directions, four intercardinal directions and in two levels (light shade; deep shade) and systematically translated in numerical values as shown in **table** 5
To translate the multiple choice, character input from participants in numerical values, the **table** was applied as follows:

Table 5: Cardinal directions and intensity of shade

Cardinal direction / intensity of shade	Light	Deep
East	0.025	0.05
South-east	0.1	0.2
South	0.25	0.5
South-west	0.1	0.2
West	0.025	0.05
None	0	0
Total:	0.5	1

Based on tree coordinates, many different open access grid datasets could have been added to augment the data in an interesting or worthy way and to allow follow up projects to choose trees from specific site conditions.
To emphasise the boundaries of the present thesis, only three were chosen, that are relevant when choosing candidates from "challenging growing conditions" in potential follow-up projects.

Table 6: Chosen datasets for the analysis

Data	**Reasoning**	**Data set properties**
Altitude	Proxy for air temperature, humidity, soil properties and thereby dry matter productivity (Gutiérrez-Girón et al. 2015; Feudis et al. 2017; Gerold 2016; Bockheim et al. 2014; Smith; Smith 2012)	Netcdf file Resolution: 0.1 degree regular grid, 30 arc seconds = appr. 1 km Units: meter
Water retention index	Indicating potential water scarcity, or flooding risks and linked to soil properties and deepness (Joint Research Center 2010; Vandecasteele et al. 2018), thereby impacting general growing conditions and dry matter productivity(Smith; Smith 2012).	TIFF file Resolution: 100 x 100 m Units: index [0,10], nondimensional creation: Oct. 2010
Daily precipitation sum	Impacting growing conditions and strongly linked with drymatter productivity (Smith; Smith 2012)	Netcdf file Resolution: 0.1 degree regular grid, 30 arc seconds = appr. 1 km Unit: mm/ l per meter² Time span: 1950-01-01 to 2024-12-31

Data augmentation and processing was realized in the free version of RStudio statistical software.
Coordinates retrieved via the location widget of *jotform* were using the reference system EPSG: 4326 as it was applying an API of google maps, which is using this reference system.

Resources of frequent use for processing this particular data in R were:

- R as GIS for Economists (Mieno 26/09/2024)
- Spatial statistics for Data Science: Theory and Practice with Paula Moraga (Moraga 21/08/2024)
- An Overview of Coordinate Reference Systems (CRS) in R, as data can be projected in different reference systems and needs to be transformed to yield accurate outputs (National Center for Ecological Analysis and Synthesis)
- Plotting "Spatial" Data with ggplot (Anderson et al. 2017)

The R Graphics Cookbook (Chang 2013) provided many important directions to plot data of a variety of types.

2.5 Evaluation of the citizen science project

Evaluation of the present project can't be covered by this thesis to the fullest, as the closing online meeting and the review of data gained from the feedback form will happen posterior to the submission.
Evaluation encircles both monitoring for project management and analysing the final projects success and impact in the end (Soßdorf et al. 2024; Fraisl et al. 2022).

Monitoring

Monitoring for project management was realized via the explicitly open feedback culture communicated, that included:

- Very accessible display of the researchers' contact details
- Repeated advice to call or write a message when any obstacle appears
- Providing a channel for short notices (Signal group channel) and representing the researchers presence by messages, photos, or questions on a regular basis
- Personalized mailing and randomized phone calls to stay informed about registered persons plans regarding assessments and reactions accordingly

Concluding Evaluation

Subgoals phrased in the project's layout should be compared to the projects outcome to evaluate goal attainment. Subgoals and validators for goal attainment are suggested in **table** 7.

Table 7: Subgoals and indicators of the citizen science project

Subgoals of the citizen science project	validator
Goal 1: Data collection for fulfilling the research goal: assessment of veteran apple trees with potential for climate resilient vigorous apple rootstocks	Descriptive analysis of data set collected through the citizen science project
Goal 2: Addressing the needs of participants	Feedback as provided in personal communications and the concluding feedback form
Goal 3: Assuring data quality	Surveying data integrity, spatial coverage and discussing means that were implemented to assure data quality
Goal 4: Assuring future data usability	Discussing means that were implemented to assure future data usability[13]
Goal 5: Fostering improvement via feedback and evaluation	Discussing precise options for improvement and phase recommendations for future projects

Feedback form

The feedback retrieved from participants played out to be of great value to improve the data security statement, understand participants needs to overcome obstacles to assess a tree and communicate appropriately.

To evaluate the success of the project from the participants perspective, a feedback form was created. The feedback form was oriented at the goals, that were set for the project in the beginning (see chapter 3.2.4: Addressing needs of researchers and participants) and oriented at best practice examples provided by Soßdorf et al. 2024.

[13] Deployment of the data in a searchable database to promote usability is taking place posterior to the submission of this thesis and will not be discussed

The feedback form was anonymous and included:

- Achievements of benefits for participants, namely “growing knowledge”, “networking” and “gain of fun and/or motivation” were queried
- Satisfaction with different elements of the project: communication and the assessment protocol
- Obstacles that hindered registered persons to assess trees
- Option to state interest in getting involved in future similar projects or follow-up projects with the opportunity to again provide an email address for contact

A PDF version of the feedback form is provided in **appendix** 14.

2.6 Materials

Software utilized throughout the present project is summarized in **table** 8 below.

Table 8: Software used in the study

Use	Name & provider	Description	Details
Viewing and editing data	Excel, Microsoft	Spreadsheet editor	Microsoft® Excel® 2016 MSO (Version 2508 Build 16.0.19127.20192) 32 Bit
Text editing	Word, Microsoft	Word processing program	Microsoft® Word 2016 MSO (Version 2508 Build 16.0.19127.20192) 32 Bit
Presentations for online meetings	Power Point, Microsoft	Presentation program	Microsoft® PowerPoint® 2016 MSO (Version 2508 Build 16.0.19127.20192) 32 Bit
Literature management	Citavi, Lumivero	Literature management tool	Citavi version 6.19 www.citavi.com
Citation facilitation	Citavi Word Add-in	Literature citations	Version 6.19.2.1
Advertising and communication	Signal	Messenger app	Version 7.58.0 www.signal.org
	telegram	Messenger app	Version 6.1.3 Licenced GNU GPL vs 3[14]
Online meetings	Zoom Workplace	Online meeting provider	Version: 6.5.9 (11873)
Data augmentation, processing and plotting	RStudio	Development environment for programming language R	Version 4.5.1 (2025-06-13 ucrt)
R Packages for data processing	Raster	Geographic Data Analysis and Modeling	Version 3.6.-32 www.rspatial.org/raster
	Tidyverse	Set of R packages with harmonized data representations	Version 2.0.0 including dplyr, ggplot2, lubridate, purr, tibble and more www.tidyverse.tidyverse.org
	Tidygeocoder	interface for getting data from geocoding services.	Version 1.0.6 www.jessecambon.github.io/tidygeocoder
	Terra	Spatial data analysis tool	Version 1.8-60 www.rspatial.github.io/terra/
	ggspatial	Spatial data framework for ggplot2	Version 1.1.9 www.paleolimbot.github.io/ggspatial
	sf	Simple feature to handle spatial vector data	Version 1.0-21 www.r-spatial.github.io/sf
	sp	Classes and methods for special data	Version 2.2.-0 www.github.com/edzer/sp
	Ncdf4	Interface to unidata netCDF files	Version 1.24 www.cirrus.ucsd.edu/~pierce/ncdf
	rnaturalearth	World map data from Natural Earth	Version 1.1.0 www.github.com/ropensci/rnaturalearth,
	rnaturalearthdata	World vector map data that can be used by rnaturalearth package	Version 1.1.0 www.github.com/ropensci/rnaturalearthdata
	Pacman	Package management tool	Version 0.5.1 www.github.com/trinker/pacman

[14] https://github.com/telegramdesktop/tdesktop/blob/master/LICENSE

	patchwork	Composer of plots	Version 1.3.1 www.github.com/thomasp85/patchwork
E-mailing, communication	thunderbird	Desktop Mail organizer	Version 4.5.1 (2025-06-13 ucrt)
Personalized mails for participants	Thunderbird mail merge ass-in	Mass mailing assistant	Version 11.2.0 www.addons.thunderbird.net/addon/mail-merge
Spell checking in e-mails	Thunderbird language tool add-in	AI Spell check assistant	Version 8.11.2 www.language-tool.org
Advertisement material design	Canva	Online graphic design platform	www.canva.com
PDF creation and managing	PDF 24, geek Software GmbH	PDF creator and editor	Version 11.25.0 www.pdf24.org
Creation of application, assessment protocol and feedback form	*Jotform*	Online form builder, survey tool, app-builder, electronic signature software	www.*jotform*.com
Data storage	Nimmerland, Nextcloud	Data secure cloud storage	www.nimmerland.de/

Datasets chosen for data augmentation is referenced in **table** 9 below.

Table 9: Datasets used in the study

Dataset	Details
Altitude	Elevation data from: E-OBS: "daily gridded observational dataset for precipitation, temperature, sea level pressure, global radiation and wind speed in Europe" Version 31.0e (Cornes et al. 2018)
Water retention index "WRI is dimensionless and takes into account the role of interception by vegetation, the water-holding capacity of the soil, and the relative capacity of both the soil and the bedrock to allow percolation of water. The influence of soil sealing and slope gradient are additionally considered."-(Joint Research Center 2010; Vandecasteele et al. 2018)	Joint Research Centre, European commission "composite indicator developed to assess the capacity of the landscape to regulate and retain water passing through it." Created: 26.07.2010 www.data.europa.eu/89h/06c3f085-c1e3-4228-949d-82a0899b8d7d
Daily precipitation sum	Rainfall data from: E-OBS: "daily gridded observational dataset for precipitation, temperature, sea level pressure, global radiation and wind speed in Europe" Version 31.0e (Cornes et al. 2018)

Acknowledgement

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3. Results

3.1 Results of literature work

Requirements imposed on climate resilient rootstocks for vigorous, standard sized apple trees

Beside characteristics that are established as being favourable for rootstocks in general or vigorous rootstocks in particular, this thesis was aiming to add characteristics that are of interest when considering circumstances that are likely to establish with proceeding climate change. As vigorous rootstocks are mainly used in extensive production settings, these low maintenance conditions need to be taken into account when characteristics for future vigorous, climate resilient rootstocks are selected.

Objectives of conventional apple rootstock breeding programs

As extracted from Korban 2021; Dhurve et al. 2023; Hanke; Flachowsky 2017; Marini 2024 & Sestras; Sestras 2023 these are as following:

- Supporting the productivity of the scion
- Disease resistance
- Sufficient cold hardiness
- (stable) Graft compatibility with (many/ most) scion cultivars
- weak vigour/ Imparting of a suitable (dwarfing) growth habit
- Precocity
- sufficient nutrient uptake and translocation
- sufficient water use efficiency
- drought tolerance
- suitable phytohormone flux
- sylleptic branching
- suitable endodormancy and chilling requirement
- cold tolerance
- stable graft union
- levelling out biennial bearing
- little tendency to produce burr knots and root suckers (which greatly depends on local conditions)

Traits supporting propagation propensity and sustained performance

As extracted from Korban 2021; Dhurve et al. 2023; Hanke; Flachowsky 2017; Marini 2024 & Petruschke 2020 these are:

- easy propagation (high germination percentage or good rooting ability), potentially recognizable by formation of many root suckers (Webster 1995)
- fire blight resistance
- tolerance to apple replant disease ARD
- tolerance to crown rot (*Phytophthora* spec.)
- tolerance to crown gall (*Agrobacterium tumefaciens*)
- root morphology for good foraging and vertical stability
- suitable interaction/adaption towards soil characteristics
- low sensitivity to viruses and phytoplasmas
- resistance to woolly apple aphids (*Eriosoma lanigerum)*
- Propagation material should be free from pests and diseases
- Resistance for apple proliferation, that is caused by a Phytoplasma

As dwarfing rootstocks are an imperative part of intensive apple production, rootstock characteristics that are needed to support the growth of standard apple trees in extensive production are not in the row of characteristics in the cited literature.

Traits that are addressing the specifications of standard fruit trees growing practices

Noticeably, literature-based exploration of breeding objectives of rootstocks for apple production on standard fruit trees is inherently difficult, as only few resources are addressing the topic. Standard apple trees and rootstocks supporting vigorous growth are nearly absent in contemporary fundamental literature and research programs about tree fruit production (cf. (Büchele 2018; Cordes; Sommer 2010; Hanke; Flachowsky 2017; Kviklys et al. 2022; Korban 2021).

The following traits are highlighted in an article about fruit and apple rootstocks by Brüntjen 2019 in the annual issue of the German Association on Pomology, explicitly referring to extensive growing practices in fruit tree meadows:

- Longevity (several decades)
- Non-sensitive to root voles
- Vertical stability
- Vigour as height

- General health
- Suitable growth habit
- Frost hardiness
- Root architecture to support vertical stability and water/ nutrient foraging
- (Fast) forming of a straight and stable trunk – this trait can be side-stepped by performing a middle-grafting
- Seed-borne, as vegetatively propagated rootstocks are described as not playing a vital role in growing standard fruit trees in fruit tree meadows anymore

Traits of "climate resilience"

Additionally to these general requirements, a "climate resilient" crop is considered to cope with several conditions that will be listed below. It should be considered that the named traits are indeed influenced by rootstocks, but by scion and rootstock x scion interaction as well.

Kopeć 2024 were summarizing the multiple stress factors, climate-resilient crops should be able to cope with:

- **Human-made stress factors** (organic pollutants, air pollutants, microplastics, agrochemicals)
- **direct effects of human caused climate change** (elevated CO_2, increased air temperature, shifts in phenology),
- **climate driven factors** (droughts, heatwaves, severe storms, heavy rainfall, hailstorm, flooding, snowless and wet winters, cold snaps, and tropical cyclones),
- **biotic factors** (pathogens, animals, and parasitic plants),
- **soil-associated stress factors** (salinity, depletion, microbiome changes, acidification/alkalization, erosion, and heavy metals).

Narrowing the scope, factors that are concerning apples in Germany and its neighbouring countries are listed below.

Drought: woody plants

Martina Flörke et al. calculated the availability of ground water for different climate scenarios for the whole of Germany in 2024 and concluded, that in the annual mean of our climate change future, water resources will be limited in many regions. Conflicts regarding the resource and federal restrictions by prioritizing water use will limit the water availability for agricultural irrigation use, especially during droughts. Additionally, water supply is not only shrinking significantly, but also inhomogeneously, with regions being affected differently. Still, a great level of uncertainty exists regarding the regional groundwater levels, with missing data and missing strategies of water usage (Donheiser et al. 25/10/2022).

Trait of interest: drought tolerance

Shift of inhabitable places in Germany

An organism's ability to inhabit a certain environment is (alongside with other factors) dependent on its temperature niche. Plants seem to be less sensitive and more generalist regarding temperature ranges than birds, butterflies and beetles (Bowler et al. 2015).

Trait of interest: temperature tolerance

Factors that are affecting woody plants in general

Heat and drought are putting trees at risk to die, as forest diebacks are witnessed in many regions of the world, with disability to maintain positive water balance, carbon starvation due to heat-induced regulation of transpiration and hydraulic failure in water transporting vessels of trees being the underlying reasons (McDowell et al. 2022).

Traits of interest: water use efficiency, ability to maintain positive water balance and avoid hydraulic failure

(Forest) trees are showing different sensitivity regarding drought conditions, with traits like height, stem circumference, vigour and volume of root system and leaf architecture altering their susceptibility (McGregor et al. 2021). Across forest biomes, drought-related mortality of trees was concluded to be promoted by two functional traits: a low density of the wood and a higher specific leaf area, when Greenwood et al. 2017 were performing a global meta-analysis, including the factors drought, temperature, biomes, phylogenetic and functional groups and functional traits.

Traits of interest: height, stem circumference, vigour, root system volume, leaf architecture, wood density and specific leaf area

Bauerle; Bowden 2011 found a significant effect of leaf width on the transpiration rate among *Acer rubrum* genotypes, but without surveying the resulting water use efficiency.

When examining drought affected trees of nine different tree species, Brito et al. 2025 found, that leaf thickness was correlated to drought tolerance – while leaf mass area wasn't. This is partly supported by Delzon 2015, reviewing the evidence between specific leaf area and forest water availability and leaf economic spectrum, respectively.
Generally, leaf's micro-morphology is playing a role in plants coping with droughts and epidermal appendages like trichomes and cuticular wax could be interpreted as a sign of adaption to water shortages
Traits of interest: leaf thickness, leaf width, leaf trichomes and cuticular wax layer

It should be considered, that due to the differences of forest and open landscape habitats, evidence of the presented studies can not be easily transferred to the situation of apple trees in *Streuobst* meadows, alleys, or agroforestry systems, but might provide a tendency.

Phenological adaption of trees
Shifts in phenology and an expansion of the period of vegetation by several days (Deutscher Wetterdienst 2023; SCHEIFINGER et al. 2025) for example forcing cherries to bloom about 10 days, and horse chestnut to leaf out nearly 30 days earlier, respectively, in Switzerland (Vitasse et al. 2022) is challenging the specific phenological plasticity of many plant species and raising the question, what geographical distribution of these species can be expected in the future (Zettlemoyer; Peterson 2021) – alongside with the question, what sites will be (the most) suitable for plant production for human needs. While focussing on central European countries, earlier leaf-out dates of several tree species could be statistically fully explained by spring temperatures coming in earlier and winter chill being altered, both caused by climate change (Zhang et al. 2022). Anyway, winter chill requirements of temperate fruit trees are supposed to still be met in temperate growing regions, while this may not be true for tropical and subtropical regions (Salama et al. 2021). Suitable rootstocks could be needed to modulate chilling requirement of high chill cultivars in some regions (Fazio; Robinson 2022).

Plant phenology is also impacted by the decrease of frequency of precipitation, e.g. deciduous trees are showing earlier leaf senescence (Zhang et al. 2025).

Wu et al. 2022 were surveying the effects of droughts and precipitation on plant phenology in autumn with satellite data of the northern hemisphere. Depending on the water household regulation strategy of plants, warm and dry conditions in autumn seasons could lead to an early leaf drop of isohydric plants, putting the balance of their long-term carbon household at risk.
Traits of interest: phenological adaption to low chill requirements and extended vegetation period, e.g. regular leaf out and normal leaf senescence

In general, isohydric as well as anisohydric strategies seem to be occurring in apple trees, having an important impact on their long- or short-term drought tolerance. Zhao et al. 2023 were observing a shift from iso- to anisohydric behaviour depending on the severity of the drought. Anisohydric behaviour was used to allow the realization of fine root expansion to forage water underground.
Trait of interest: water use strategies (an/isohydric)

Apples temperature niche
Meza et al. were modelling temperature-adaption limits to climate change in different scenarios of temperate perennial fruit crops in 2023. Their findings pointed out, that the northern hemisphere would still be suitable to grow temperate perennial fruit crops under SSP 5 – 8.5, as well as SSP 1-2.6 scenario – at least temperature-wise. Anyway, their findings also pointed towards a substantial restructuring of the global production, as suitable sites to grow perennial fruit crops would vastly decrease in the southern hemisphere.

Mihaljević et al. 2025 suggested factors to be adapted in future rootstock breeding protocols, that were providing information about apple rootstocks heat tolerance and differences in heat tolerance were found for M.9 and G.210 rootstocks.

Apples chilling requirements (for most cultivars) are expected to be met in Germany, while apple production in mediterranean countries, especially France, might be confronted with chill portions that low, that extended windows of bloom and harvest would appear, if adaption isn't happening on time (Legave et al. 2016). Genetic markers that could be used to select apples with low chill requirement in future breeding projects were identified by Lempe et al. 2023, for example. Shifted harvesting windows are predicted by Hassan et al. 2024 due to long term high temperature and CO_2.
Traits of interest: temperature niche, chilling requirement, phenology

Simultaneously, apple rootstocks tolerance for cold climates and waterlogging should not slip off the tray of breeding efforts, to be prepared for cold climate and high precipitation scenarios (van Westen et al. 2024).
Trait of interest: frost tolerance, waterlogging tolerance

Drought: apple
Schliebner et al. were summarizing research about drought resistance of (mainly apple) fruit trees in 2023. In 2022 and 2023, several markers (expressional factors, proteins, genes) had been identified, that could be found in different apple species and were active under drought conditions (Qin et al. 2022; Yang et al. 2022a; Feng et al. 2023). Linked to these marker genes, traits like a drought tolerant photosynthetic activity, reduction of stomata density and thereby reduction of transpiration, as well as little damage caused by shrinking and wilting of roots and shoots, ongoing growth despite dry conditions and fewer lesions of leaves due to an effective prevention of accumulated harmful substances. “Climate resilient” trees were less sensitive to forcing conditions after witnessing dry conditions during induction phase, which is useful to side-step damage by late frost events. Schliebner et al. recommended to work with these phenotypical as well as molecular markers to identify trees, that are less affected by droughts.
Traits of interest: photosynthetic activity under drought conditions, stomatal density and transpiration rate under drought conditions, growth under drought conditions

The importance of water use efficiency is therefore on the rise. Unfortunately, there isn’t an easy answer to be found regarding the link between leaf morphological traits and water use efficiency: Bassett et al. 2011 were stating for *Malus sieversii*, that genetic adaption to drought conditions might only result in biochemical, transport of water, carbon or oxygen, *without* expressing morphological markers that could be used for visual selection (e.g.: leaf size, stomata size/- arrangement).

Bhusal et al. 2025 suggested, that there might be cultivar specific drought strategies, some being profitable for long, other for short term drought conditions and therefore useful for different production settings. They described hydraulic resilience and stomatal control as favourable traits for high density plantings. Reduction in leaf size, structural leaf enforcement in trade-off for photosynthetic efficiency was another potential reaction of *Malus* x *domestica* cultivars to encounter drought conditions. Similar results were presented by Lauri et al. 2016, describing, that different apple genotypes showed different responses on different levels of drought, with genetic disposition and phenotypic plasticity playing a role in adaption.

Reducing stem growth in thickness and forming smaller leaves to avoid losses and maintain photosynthesis, were concluded to be key strategies for apples in their experiments. The existence of different, probably long- and short-term relevant strategies for apple rootstocks to cope with drought, was concluded by Tworkoski et al. 2016 as well.

Traits of interest: effective drought adaption strategy (long term / short term), stem circumference, leaf size

Sun et al. 2022 ranked leaf morphological responses as indices with the membership function method and searched for correlations to drought resistance traits, like net photosynthetic rates. Interestingly, leaf thickness, palisade tissue thickness, sponge tissue thickness, and chlorophyll content were significantly higher in the rootstock cultivar with highest drought resistance.

Traits of interest: leaf thickness, palisade tissue thickness, sponge tissue thickness, chlorophyll content under drought conditions

To add another perspective, the findings of Wang et al. in 2024 and Yang et al. (2022b) should be taken into account: Sufficiently vigorous growth of apple roots seems to be needed, to forage for deep soil water and maintain important physiological processes to eventually be able to adapt to permanently reduced water supply.

Traits of interest: root vigour; ability to forage soil water

As drought stress is often coupled to salt stress, tolerance of soil salinity is an important feature of future apple rootstocks. Verma et al. 2024 reviewed the state of knowledge and gathered candidate genes that are involved in apples responses to salinity (and drought) stress.

Trait of interest: salt tolerance

Excess water

Waterlogging conditions due to severe rain falls, not only, but especially during winter, is predicted to increase in severity and frequency. (Brasseur et al. 2023). Effects on apple trees under waterlogging conditions in an irrigation-controlled experiment were defoliation, decrease in trunk cross-sectional area and dry weight as well as lowered photosynthetic rate and stomatal conductance (Choi et al. 2020). Apples under waterlogging conditions were surveyed by Bhusal et al. 2020; Choi et al. 2020, concluding significant differences in different rootstock’s influence on stomatal conductance, photosynthetic rate and vessel characteristics. Richard P. Marini; Gennaro Fazio 2018reviewed research on apple rootstock’s abilities to withstand waterlogging conditions and reported, that rootstock cultivars are differing in this trait.

Trait of interest: tolerance for waterlogging

Apple and late frost events

An increase in risks associated with late frost events is estimated for a third of the European continent. Reasons are acceleration of tree's phenological development in spring (earlier bloom dates), concurring with a low certainty in prediction of late frost events - an uncertainty, that is multiplied by unprecedented weather patterns and extreme weather events, that could be caused by climate change (Lamichhane 2021). Vitasse et al. 2018 surveyed the temperature changes of Switzerland and found, that fruit tree's phonology had advanced faster, that the date of last frost in spring, making frost damage just as likely or even more likely, than in the past, especially in high elevations.

Additionally, apple trees encountering mild water stress, might even break buds earlier, as they seem to be more susceptible to forcing conditions in spring – making damages by late frost events even more likely (Fernandez et al. 2020).

Phenology models to predict (apple) trees blooming dates (e.g. to manage frost sprinklers in conventional apple plantings) are tending to fail, as they normally rely on historical phenological evidence, that doesn't reflect contemporary conditions. For example, unusual warm winter seasons are limiting the accuracy of the PhenoFlex model (Fernandez et al. 2022).

Traits of interest: late frost tolerance and blooming date, blooming date depending on water stress experiences

Climate change will confront fruit (and apple) production with heat and extreme sunlight that leads to sunburnt fruit (Flachowsky; Töpfer 2021; Torres et al. 2013). Duan et al. 2015 were able to pin down apple leaves' thermotolerance to adaptions around the photosynthetic apparatus, that are usually taking place when temperatures are shifting to high summer levels in early summer.

Traits of interest: leaf heat and sun tolerance

To assure effective flower pollination and fruit setting, rootstocks for pollinator trees should have a favourable influence on pollen germination rates and pollen tube growth length, as conditions for pollen might become more difficult in the climate change future, due to desiccating of the flowers pistil and the pollen itself in dry, hot conditions. (Zebro; Heo 2024)

Traits of interest: flower's tolerance to drought and heat

Indirect effects on apple trees, that are caused by new weather patterns and climate change

Not only direct damage of fruits by storm, hail or excess water supply (e.g. bursting cherries) is suggested to be a negative effect of climate change (Brasseur et al. 2023) – long periods of warm and wet weather could increase the prevalence of fungus diseases as well. Apple's diseases that are caused by fungal pathogens are expected to thrive under climate change conditions. Marssonina blotch, apple scab and black rot canker (*Diplodia* spec.) are fungal diseases, that will gain in importance (Augustenberg 2025).

Traits of interest: tolerance or resistance against fungal diseases

Ruess 2020 are highlighting the effect of long periods of heat and drought on fruit trees, beside directly impacting yield and plant health: the potential of causing alternate bearing, a major problem in professional fruit production. Summarizing the challenges of our climate change future, they predicted a shift in plant varieties that will be grown in Germany, focussing on scion varieties.

Traits of interest: alternating/ biennial bearing

Climate change will confront fruit (and apple) production with biotic stress via new pests (Flachowsky; Töpfer 2021; Skendžić et al. 2021).

As warmer temperatures are shifting the areas where plant pests can overwinter, this is potentially correlated with plant pests pesticide resistance (Ma et al. 2021). Additionally, the warming may exacerbate plant diseases by "enhancing commensal interaction of co-infesting insect vectors" (Zhu et al. 2023), which was studied for two co-infesting *Drosophila* species, for example. Göding 2021 was expecting an increase of the following insects' pests, that are relevant for apples: codling moth (*Cydia pomonella*), apple maggot (*Rhagoletis pomonella*), shield bugs/ apple stink bugs, and sap consuming insects and insects harming stem, bark and woody parts, like large shothole borer (*Scolytus mali*). Schneider; Rebetez 2023 are confirming this general trend for Switzerland, specifying, that insects that produce several generations per year will be on the rise, as they could establish additional annual reproductive cycles, hence causing more damage. This is true for the codling moth, for example.

Traits of interest: Susceptibility for insect pests

Fireblight is also benefitting from climate change conditions (Görrissen 2008), as well as apple proliferation and its vector insect (*Cocopsylla picta*).

Traits of interest: tolerance/ resistance regarding fire blight and apple proliferation or bacterial and phytoplasma caused diseases in general

Even root voles (*Arvicola terrestris*) are expected to realize increased reproductive cycles in a warmer climate, exacerbating the risk of damage at newly planted apple trees, when the rodent is inhabiting the scene (Umweltbundesamt 2019).

Also, climate change is allowing alien plant species to immigrate, potentially becoming invasive and causing additional stress in natural and agricultural ecosystems (Fahad et al. 2024).
Traits of interest: attraction of root voles; competitiveness against neighbouring plants

When selecting these objectives whilst focussing on specific requirement for extensive management practices for apples, this leads to a set of characteristics, that can be assessed by citizen scientists and can therefore be integrated into the assessment protocol, that is described in the methodology section.

Potentials for future breeding prospects embodied by veteran apple trees

Very old trees are expected to possess a superior set of genetic information, that let them survive for a century or longer. This set of genetic information is preserved in old, living trees and could serve as a valuable genetic resource (Begemann; Vögel 1995, p. 119). Looking back at the historical development of rootstocks in Germany and neighbouring countries, apples were mainly grafted on seedlings of unknown, unique identity, very likely being progenies of landraces or hybrids of wild apples and landraces of different origin, sometime even from other countries.

With the characterization and restoring of a virus-free status of the dwarfing 'Paradise' rootstock-types taking place in the late 19th and early 20th century and taking into account the economic development of Germany in this period of time (Richard P. Marini; Gennaro Fazio 2018), trees planted in the 1930’s or earlier can be considered to be grafted on such a unique rootstock. These “veteran”, or „Methuselah“ apple trees are of interest due to their cryptic, unknown genetic traits, outstanding longevity, that could be linked to traits, that are supporting good vitality throughout their existence. Additionally, 100 years are assumed to be old age for an apple tree, and they are prone to vanish by die-off soon and should be surveyed soon, to allow a preservation (Schwärzel 2000).
Trait of interest: of old age, planted not later than 1930

Many of the old landraces that may be involved in the existence of veteran trees’ rootstocks have never been used for professional breeding programs, although they are expressing favourable characteristics (Bannier 2016; Ritthaler 24.08.2024; Lazaridi et al. 2024).

Reedy et al. 2014reported, that landraces of apples lived up to new recognition by Italian farmers, as they were less prone to diseases that were becoming more relevant with climate change – but also due to their taste and heritage. Raggi et al. 2022 even founded the first European database on landraces, to allow protection and fostering usage of landraces, including apple.

Apple is a cross-pollinated and self-incompatible plant, that has undergone several interspecific hybridizations throughout its long history. Genetic diversity is easily created whenever different germplasms' flowering, fruiting and seedlings growth are not actively disrupted. (Korban 2021) Landraces have undergone the process of domestication, therefore having different characteristics than wild plants. While wild plants genetics are considered to contain more unfavourable than favourable genetic variability regarding their usability for crops, which makes steps of "pre-breeding" inevitable, landraces are already of constrained variability, due to the process of domestication (Becker 2019a).
Thereby, chance seedlings originating from existing apple cultivars have gone down in history as popular cultivars several times (Korban 2021).

Gross et al. 2018 were surveying and trying to identify genetical relatedness of unknown apple trees in northern Minnesota, utilizing a wet of 9 SSR markers. After scanning the genetic diversity and identity of 330 highly diverse apple trees, of which no more than 76 could be matched with named cultivars, they stated the high value of local breeding programs, that are enhancing biodiversity by introducing new germplasms. Some of the tree individuals they found were in use and considered to be valuable by their owners, others, wild seedlings populating a formerly managed orchard, showed traits that seemed worth to be evaluated regarding their suitability for new cultivar's development.

Wild plants and early landraces are valuable sources of genetic diversity, "because natural selection has already tested more options than humans ever will. (Cortés; López-Hernández 2021, p. 1). Cortés; López-Hernández are arguing, that "isolated pockets of cryptic diversity may still persist in remote semi-arid regions", making habitat-based population guided collections for genebanks a promising endeavour.

Plants that have witnessed extreme natural weather events, partly referred to as negative "signature years" that caused significant growth depressions due to hard winters or persistent drought. Standard apple trees and rootstocks are potentially successfully growing under these challenging conditions, worth being considered as a genetic resource (Schwärzel 2000; Feuerhahn 2000).
Trait of interest: challenging growing conditions (historically and contemporarily

Denney et al. 2020 are highlighting the big impacts of small spaces, namely the contributions of micro-environmental variation to population's diversity. They pronounce, that conditions of small impacts can be significantly different from the general wider area's conditions, though remaining invisible, when (only) spatial grid data is used to find places of interest for germplasm collection.
Trait of interest: challenging very local conditions

A generalized trait of interest is "vitality", that can be observed as the outcome of upstream, probably obscured processes and traits (Heidenreich et al. 2024). As pruning generally supports vitality (Schliebner et al. 2023; Bartha-Pichler et al. 2005)and should therefore be taken into account when vitality is assessed.
Traits of interest: tree vitality

As mentioned in the state of research section, the European wild apple/ crab apple and hybrids of domesticated apple and crab apple have historically been used as rootstocks could make up a share of rootstocks that are assessed in this project. As wild apples and habitats populated by wild apple have been documented in Germany during the last decade (Höltken et al. 2014), non-grafted wild apples should be excluded or at least marked in terms of this project to avoid duplicates and focus on unknown veteran apple trees.
Trait of interest: not a wild apple

Potential of veteran apples were already surveyed in Germany
In 2000, Feuerhahn successfully regenerated several different fully mature rootstocks of an apple tree alley in the German federal state of Brandenburg, that was estimated to be about 200 years old. The objective was to allow the usage of these obviously long living, robust and "bullet proof" rootstocks to regain genetic diversity for vigorous, standard sized fruit trees. The genetic and cluster analysis were conducted by Hilmar Schwärzel in 2000 and revealed "a spectrum, that was wider than the scion cultivar's spectrum above ground" (Schwärzel, personal communication, 2025). These clonally propagated rootstocks emerging from their study were recommended to be used as rootstocks and to be therefore included in nursery's supply. Also, it was suggested to induce inflorescence in an isolated area to assemble a subset of the gene pool, that had been present in the early 19th century and to allow to study their characteristics and qualifications as parental plants for future seedling rootstocks in depth (Feuerhahn 2000, p. 115).

In 2025, four of the regenerated rootstocks were rediscovered, after they had been saved into a forest area close to city Eberswalde, to preserve them for future uses. Although they were not in best condition due to their shaded position and sandy soil of the area, they were still alive and samples were taken for marker analysis. Also, scions were cut and grafted onto rootstocks to produce replica of these unique germplasms.

The origin of the trees, the 200 year old alley, is partly not existing anymore Unfortunately, the recommendation of Feuerhahn didn't become reality, partly due to missing funding for a follow-up project (personal communication, 2025).

Tools of citizen science that could be utilized to collect valuable data on veteran fruit and apple trees

Citizen science is defined as "the participation of people in scientific processes who are not institutionally bound in that field of science" (Bonn et al. 2016; Bonn et al. 2022). Different levels of participation can be described as, according to Haklay 2013, "crowd sourcing" (1), "crowd intelligence" (2), "participatory science" (3) and "collaborative science" (4).

Higher levels of participation are covering: Definition of the scope of research projects, the right to be heard when methodologies are chosen, data collection, data interpretation supported by professional scientists, for example.

Beside the level of involvement, the general type of a project could also be used to define a citizen science approach: A project could be just ordered and watched by citizens, citizens could be contributing in a strictly predesigned way to a contributive project that was developed by scientists only, collaborative projects could involve citizen scientists in some essential steps of the research project, co-creative set-ups could be accompanied by citizen scientists in every aspect and even cooperative projects are possible, with citizens conducting their own research voluntarily and independently and feed the results into a professional project (Vohland et al. 2021). Adjusting the type of project to concerned research topic and goals, layouts ranging from simple to elaborate tasks for participants are just as possible as mass approaches to systematic targeting of very specific target groups (Pocock et al. 2017).

Especially biodiversity monitoring is, according to Vohland et al. 2021, profiting from the possibility to reach spatial and temporal coverage that is often needed to gain reliable observations by participants being the "sensors" that are travelling to the places of interest and assessing the endeavoured observations for scientists. Genetic diversity focussing on agriculture and food science specifically has been the subject of several international citizen science projects (Ryan et al. 2018).

Ahlawat et al. 2022 were summarizing projects taking place in India, that were focussing on the collection of plant genetic resources. Collection of landraces and trait-specific collection of these helped augmenting the Indian collection of germplasm accessions with heat- and drought tolerant and mildew immune crops, just to name two examples out of a row. Mapping of the accessions also allowed to identify spatial gaps and breeders are showing interest in accessions with desirable traits.

To meet the precondition of suitability of a citizen science approach to address the research questions of the present project, considerations suggested by Fraisl et al., pp. 2–3 were undertaken:

- Will participants help to achieve the desired results?
- Could an approach at the same time benefit participants?

Meeting both conditions, according to Fraisl et al., makes a citizen science approach likely to be suitable. Suggested factors for the decision are:

- Research questions
- Spatial and temporal scale
- Type and amount of data needed to obtain results
- Level of expertise required to collect the data
- Training and coordination efforts needed
- Target groups of the project (e.g. participants, policymakers, funders, scientific and practicioner communities)
- Requirements of human resources (skills, tasks, responsibilities)
- Requirements of equipment, travel or training to fulfil tasks
- Funding and available resources

Fraisl et al. 2022, pp. 3–4 are highlighting, that “Projects that may be unsuitable for citizen science approaches could be those that require the use of expensive or highly technical equipment, or projects that demand a great deal of time commitment […].”

Fraisl et al. 2022 where operationalizing the progress of citizen science projects in the field of ecology and environmental science in 6 stages:

1. Identifying the problem
2. Determining if citizen science is the right approach
3. Designing the project
4. Building the community
5. Managing the data (= planning, collecting, assuring, analysing, describing, and preserving, integrating)
6. Evaluating the project

(Fraisl et al. 2022, p. 4)

Citizen science is depending on a good strategy to reach out to potential participants, by utilizing an effective recruiting strategy. Suitable candidates should be approached with a strategy that is oriented on the defined target audience. The precondition is the definition of the target audience. This approach includes designing material that is attractive and appropriate for the targeted group, taking their interest, knowledge, age and expected habits of communication into account, for example.

In case a specific group is aimed for, suitable “multipliers” are recommended, to use their network and coverage to spread the announcement of the project. To win suitable participants for a project and keep them motivated, incentives should be given und clearly communicated. These as well should be suitable for the target group.

Monitoring during the projects progression is supporting the steering and controlling in citizen science projects, by considering the needs and characteristics of participants, which can result in significant improvement of the overall outcome of the project. (Soßdorf et al. 2024)

The importance of assuring data quality and data management is highlighted in the White Paper Citizen Science Strategy 2030 for Germany (Bonn et al. 2022) to make the most of the potential embodied by citizen science approaches. At the same time, the authors are underscoring, that citizen science produces valid data – when data quality is assured by the researchers. They are suggesting “developing guidelines on data quality, establishing standardised procedures for data collection, training and supporting participants, collecting evidence (e.g. through photos) and experts assessing the collected data” (Bonn et al. 2022, p. 63).

Fraisl et al. 2022 are summarizing typical concerns regarding the quality of data that is collected n citizen science projects and offering procedures to sidestep them. Trainings for participants, providing guidelines that are adapted to participants skills, controlling and filtering of the data by experts and evaluation of participants skills, handing structured protocols of sampling are valid options for the present project as well, that could limit inconsistency in protocol application, false or unrepresentative sampling.

Quality of data gained from the citizen science project could also be improved by adding redundancy and offering workshops to allow participants to train them, close gaps in their knowledge, get in touch on the personal level to encourage them to reach out in case they need help to carry out the tasks of the project The latter is characteristic for citizen science projects with a higher level of participation.(Soßdorf et al. 2024).

Transparency of data origin and methodology of obtainment is stressed by the White Paper Citizen Science (Bonn et al. 2022) in order to establish trust of the scientific society in this type of data.

Data quality is linked to future usability, that is making sure that data can unfold a long-term impact and can be integrated in further studies. The FAIR data principles are providing a framework for data publishing, that is supporting interoperability and interpretation of the data (GO FAIR 21/01/2022).

Evaluation in citizen science in encircling monitoring for project management and concluding evaluation to validate goal attainment and improve future projects.

Feedback throughout the project is crucial for monitoring and managing reasons.

To evaluate the overall success of a citizen science project, counts of participants, participation in events and overall data collection incidences as well as feedback questionaries are suggested by Soßdorf et al. 2024. For more differentiated feedback, questions should cover different aspects of the project, like “contentedness of participants with offered guidelines or contentedness with specific episodes in the projects progression“. Concluding evaluation is requiring to phrase goals to be achieved throughout and in the end of the project (Soßdorf et al. 2024).

As citizen science is also aiming to fulfil the participants needs, to eventually reward their engagement, effects of the project on participants should also pe part of the evaluation (Soßdorf et al. 2024, pp. 42–43).

Describing and preserving the data is often linked to legal issues and data safety (Fraisl et al. 2022, p. 12). The Berlin Museum für Naturkunde 2020 is offering guidelines to handle legal issues in citizen science projects. Information concerning the insurance coverage of participants while performing field observations as well as their rights regarding their personal data and the projects concept to assure data usability and data sovereignty of participants at the same time should be gathered and communicated effectively to ensure every participant to be aware of it.

Results to be integrated into the methodology of the present work

Applying the nomenclatures of Haklay 2013, the present projects the level of participation is defined to be between 2 ("crowd intelligence") and 3 ("participatory science"), as advanced people with experience in the field of veteran apple trees are an inevitable element and are feeding their experience into it, which is welcomed to contribute to the overall outcome.

Referring to the constant engagement and experience of German pomologists and associated groups like fruit tree wardens, that was mentioned in the introduction section, they are set as targeted group for recruiting suitable, advanced participants. The classification according to Pocock et al. 2017 can therefore be described as systematic instead of mass participation and the data collection will have the tendency of elaborateness, which should be in the range of the target groups abilities.

Especially the "big impact of small spaces" (Denney et al. 2020) is making on site observations very valuable instead of using grid data only. The selection of apple trees for assessments should be trait specific, with suitable criteria to choose trees that are likely to hold potential in accordance with the research goals.

Apple trees are potentially growing in sensitive settings like private gardens or nature preservation areas. This instance could get in the way of future usage, data confirmation or further studying, due to (future) accessibility of the trees due to data privacy of the owners or of those, who are looking after the tree. To protect private data and give control regarding the use of the assessed trees to the participants or tree owners, an appropriate policy for data safety needs to be set up and communicated.

Speaking in the 6 stages suggested by Fraisl et al. 2022, the procedure described in **table** 10 appears suitable to be applied to fulfil the research goals of this project:

Table 10: Stages and procedures of the citizen science process in this study

Stage	Participation	Coverage in this thesis
1: Identifying the problem	Not officially, as the problem was partly identified during conferences with many potential and future participants present	As literature work (introduction, results of literature work
2: Determining if citizen science is the right approach	No	Results of literature work
3: Designing the project	Partly, through feedback	Detailed in methodologies and materials section
4: Building the community	yes	Yes, for mor details on practical elements see methodologies and materials section
5: Managing the data (= planning, collecting, assuring, analysing, describing, and preserving, integrating)	Yes, in collecting, assuring, and preserving and integration in the future	Partly: planning, collecting, assuring, analysing, describing is covered during the time span of this thesis, but preserving and integrating is solely described and will be realized in the future
6: Evaluating the project	Partly: feedback questionnaire was designed without involvement, but open space for feedback and discussion on future directions during the final online meeting is allowing more involvement	Partly: information on participation, spatial coverage and more is described and initial findings of the final questionnaire is mentioned without graphical data presentation; final online meeting with participants will take place after thesis submission

For a detailed description of the citizen science project and the design of the assessment protocol that was merged from veteran tree’s traits of interest and capabilities of advanced citizen scientists, please consider the methodology section.

3.2 Results obtained in the citizen science project

Data to evaluate the citizen science project

Figure 1 is displaying registrations in the project during its run time. Interested persons could register in the project via a *jotform* form and would be informed about the current progression of the project and their options to get involved. Registration form on *jotform* was open from 10th of February ongoing. People started to register in late February, when advertising via multipliers had started and numbers were growing beyond the time span of tree assessments (1st of May to 31st of July) and until the submission date of this thesis. Numbers of registered persons exceeded 210 registrations until early September (data not shown).

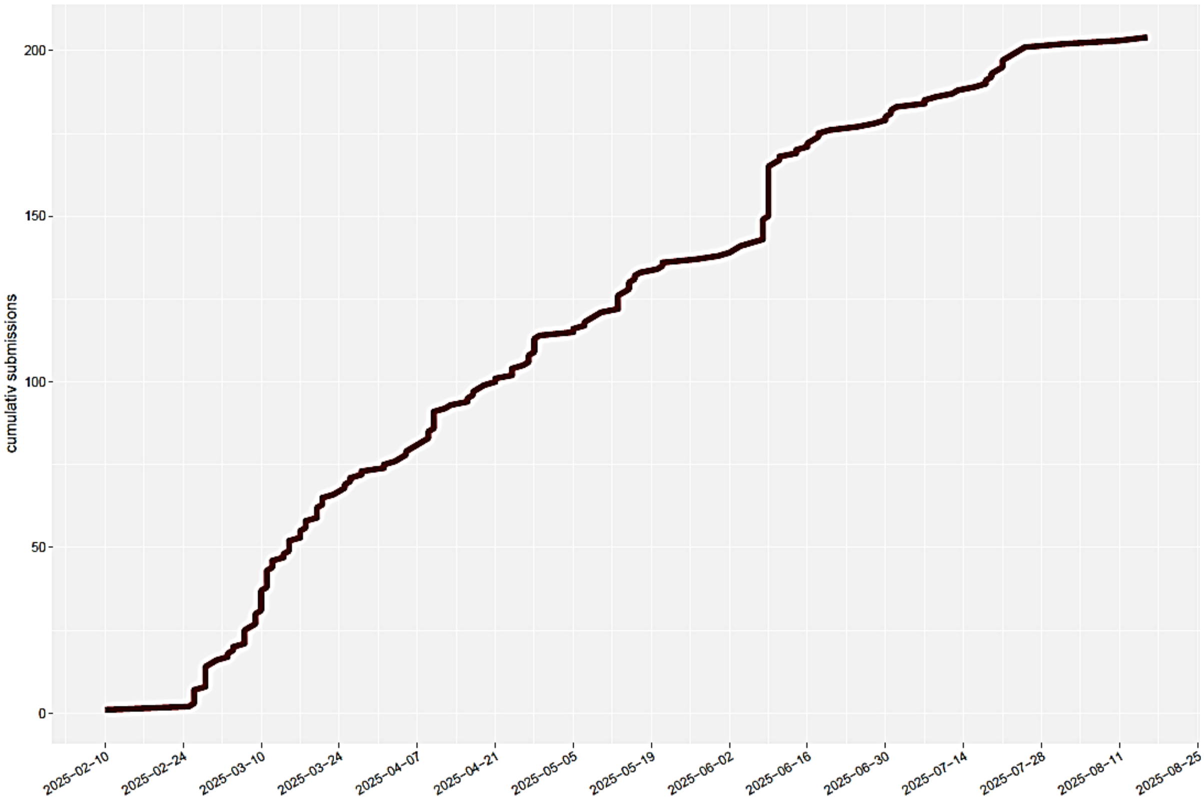

Figure 1: Submissions of registration form during project run time.

Registration form on *jotform* was open from 10th of February ongoing.

Figure 2 below displays home counties of people registered in the project until mid-August 2025. Most regions of Germany are covered, clusters appear to be present in the state Baden-Württemberg. Gaps of coverage seem to be between the cities of Hamburg and Berlin as well as around Leibzig, the forest of Thuringia, close to the border to Belgium and Luxembourg. Few registrations were scattered and isolated submitted from Poland, Slovakia, Hungary, Austria, Switzerland, France and the Netherlands.

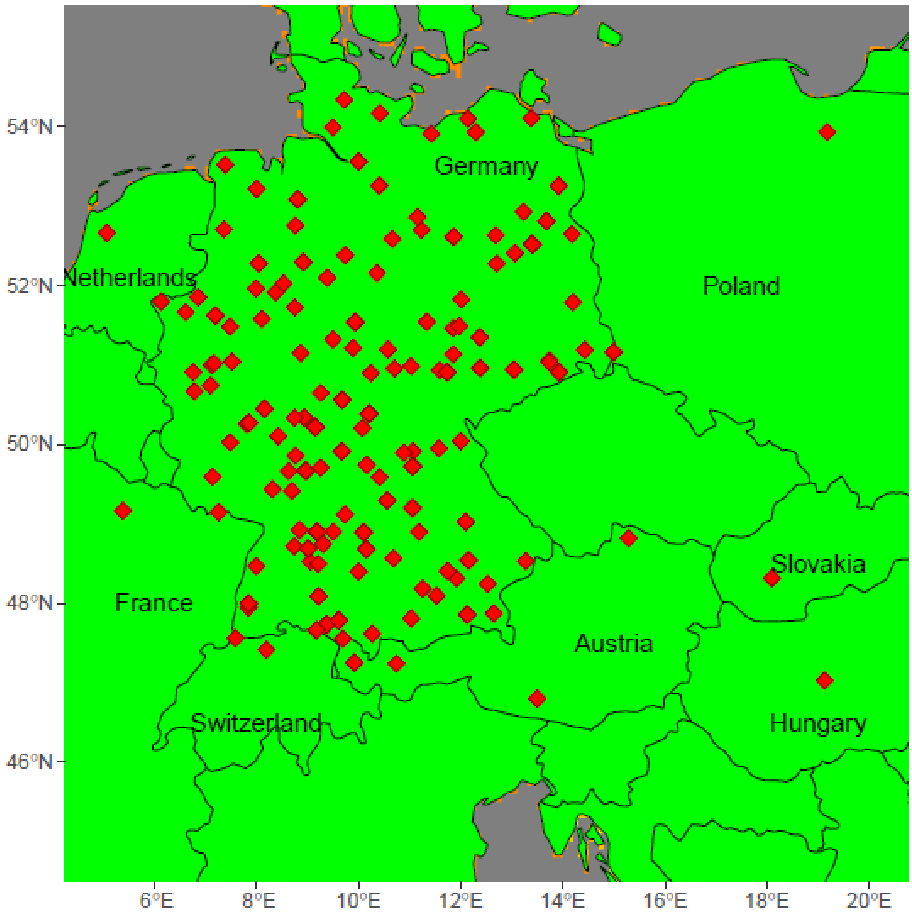

Figure 2: Home counties as stated by persons registered in the project

Figure 3 below displays submissions of veteran tree assessments over the time span of the data collection phase. Nearly no Submissions were made until late May, representing a lag phase of nearly a month's time. Less than 25 submissions had been handed in until the second half of June. At his point, reminding emails and phone calls were set up by the project management to investigate the reasons for low counts of submissions. Submissions climbed to 50 until the end of June and began growing more constantly in early July, reaching a total of slightly more than 150 by end of the data collection phase at the end of July.

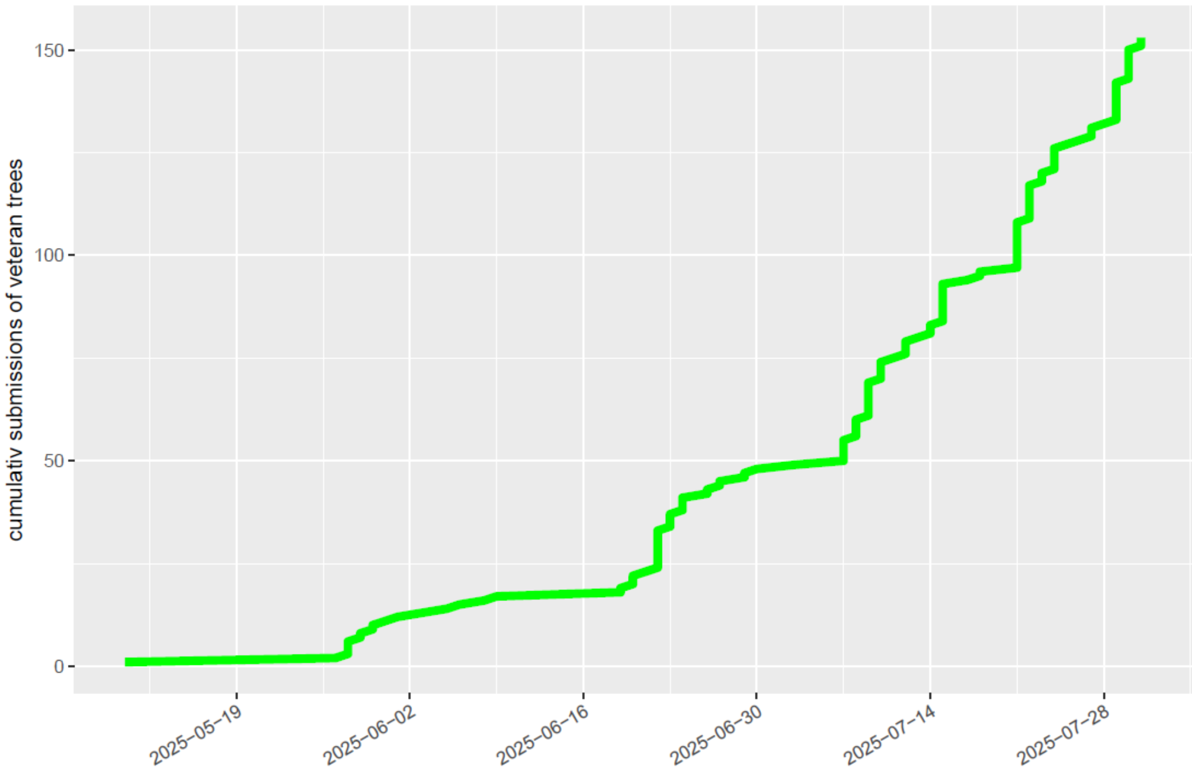

Figure 3: Completed veteran tree assessments during phase of data collection

The assessment form was open for submissions from 1st of May until 31st of July.

Figure 4 below displays interests of persons that just registered in the project compared to interests of those who submitted assessments of trees. Supporting persons, that helped assessing the trees, reported trees so others could assess them or contributed in any other way are not visible, as only one person could fill out the assessment form and put in their details and interests. Removing duplicates revealed, that out of nearly 200 registered persons no more than 32 different ones submitted trees. Persons that were solely registered stated as following: 36 % stated to be interested in "practical use/ horticulture", 29 % stated "preservation of nature" to be of interest for them, 19 % put in "research" as an important interest. 16 % couldn't find their interest in the offered options or didn't want to comment.

For persons that submitted data, "practical use / horticulture", "preservation of nature" and "hobby" were stated in equal shares of 28 - 29 %. 10 % put in "research" as an important interest, 4 % couldn't find their interest in the offered options or didn't want to comment.

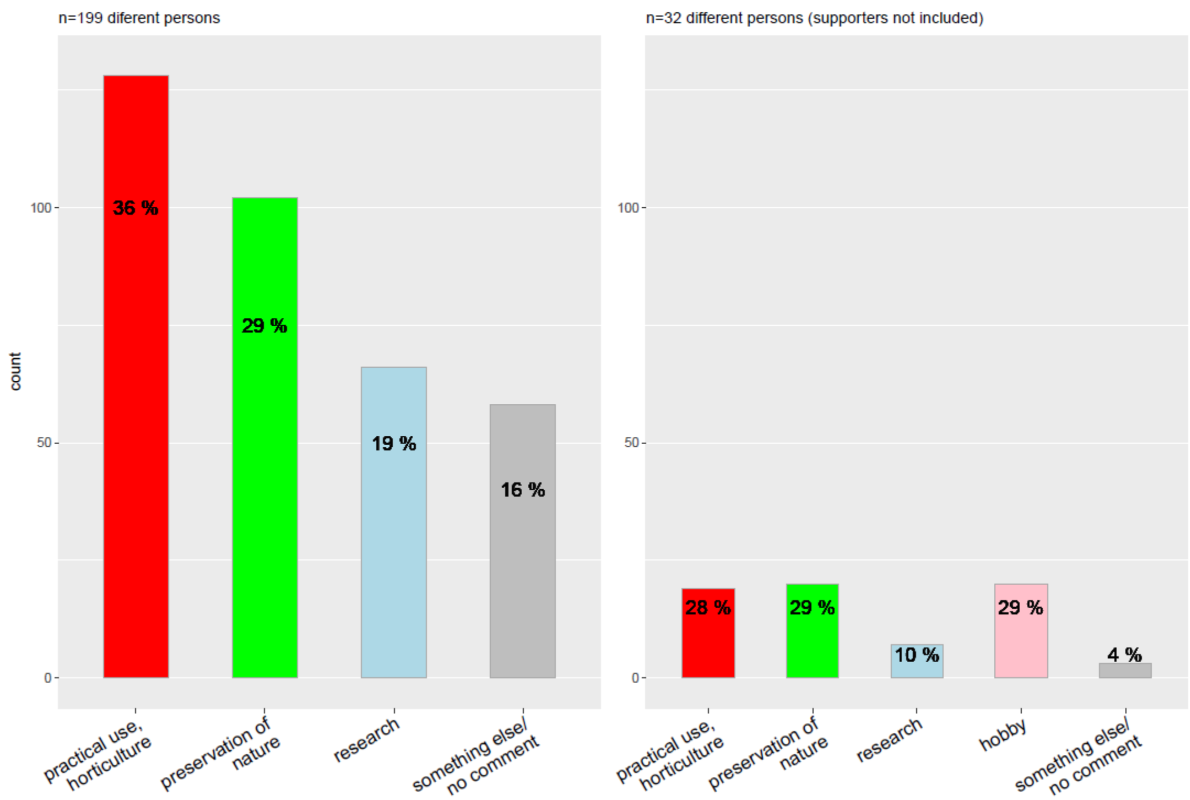

Figure 4: Counts and interests of 199 persons registered in the project and interests of 32 different persons submitted assessments of trees

Interests of persons that assessed several trees were only once. To state interests was a mandatory, multiple choice question, the option "hobby" was not available in the registration form. Percentages are calculated as share of all answers provided.

Feedback questionary

The feedback questionary was not closed until this report was submitted, but 56 answers that were submitted until 5th of September are provided in **appendix** 15; personal data not included.

The questionary was used by persons that had been registered but did not assess a tree as well as by persons, that had assessed one or several trees.

Regarding their recruitment, most persons in this incomplete sample said, they were informed by “newsletters, websites or messages emerging from an association, network or group” they already had been associated with. Fewer people were informed by friends, acquaintances or colleagues and nearly nobody became aware of the project via newspaper articles and the citizen science platform “mitforschen.de”.

Those that had stated they had been assessing trees were asked for their opinion on the assessment tool and all grades from 1 (very good) to 6 (very bad) were given, with most responding with grade 2.

Those that did not assess a tree mostly stated that they couldn’t make the time to do so, fewer could not find a suitable tree that was meeting the criteria and a minor share of less than 5 persons mentioned the assessment tool itself and concerns regarding data safety as reasons. About the same count of persons had simply not heard of the project on time to add their tree.

When asked about their opinion on the communication between project management and themselves, the grades 1 (very good), 2, 3 and 6 were chosen, with grade 1 and grade 6 being the most prevalent. Anyway, free text descriptions of communication were either positive, very positive or revealed, that persons had simply not received any messages. One person stated, information could have been more compact and one described the assessment protocol as being way too voluminous.

When asked for rewarding outcomes for themselves, most persons stated that they had learned something new. Slightly more people giving feedback said that they did not feel like they were interconnected to others in their field of interest, compared to slightly less people stating that they did feel like their interconnection was fostered. The vast majority stated, that they had fun or gained motivation from the project and this answer seemed to be independent of the question if they had assessed a tree themselves.

45 out of 56 persons said, they would like to be informed about or contribute to follow up projects that are working in the same directory and left their contact details to allow communication.

Data describing the assessed veteran apple trees and rootstocks

The data processed into graphics only constitutes a share of the different types of data that was collected in the project. A complete overview is provided by the layout of the assessment protocol and the exported data that is accessible in digital **appendix** 13.

Figure 5 displays the 154 trees that were assessed within the phase of data collection in the present project, plotted on a map of the elevation and distinguishable by age. Trees that were assessed were located in different regions from Schleswig-Holstein to the southern border to Switzerland and Austria. Isolated trees were assessed in Switzerland, Austria and Slovakia. The whole area of Germany was not covered, instead, dense clusters are visible in few areas. The assessed trees assessed were of various ages. Trees were assessed in areas elevated close to 0 to about 1000 meters.

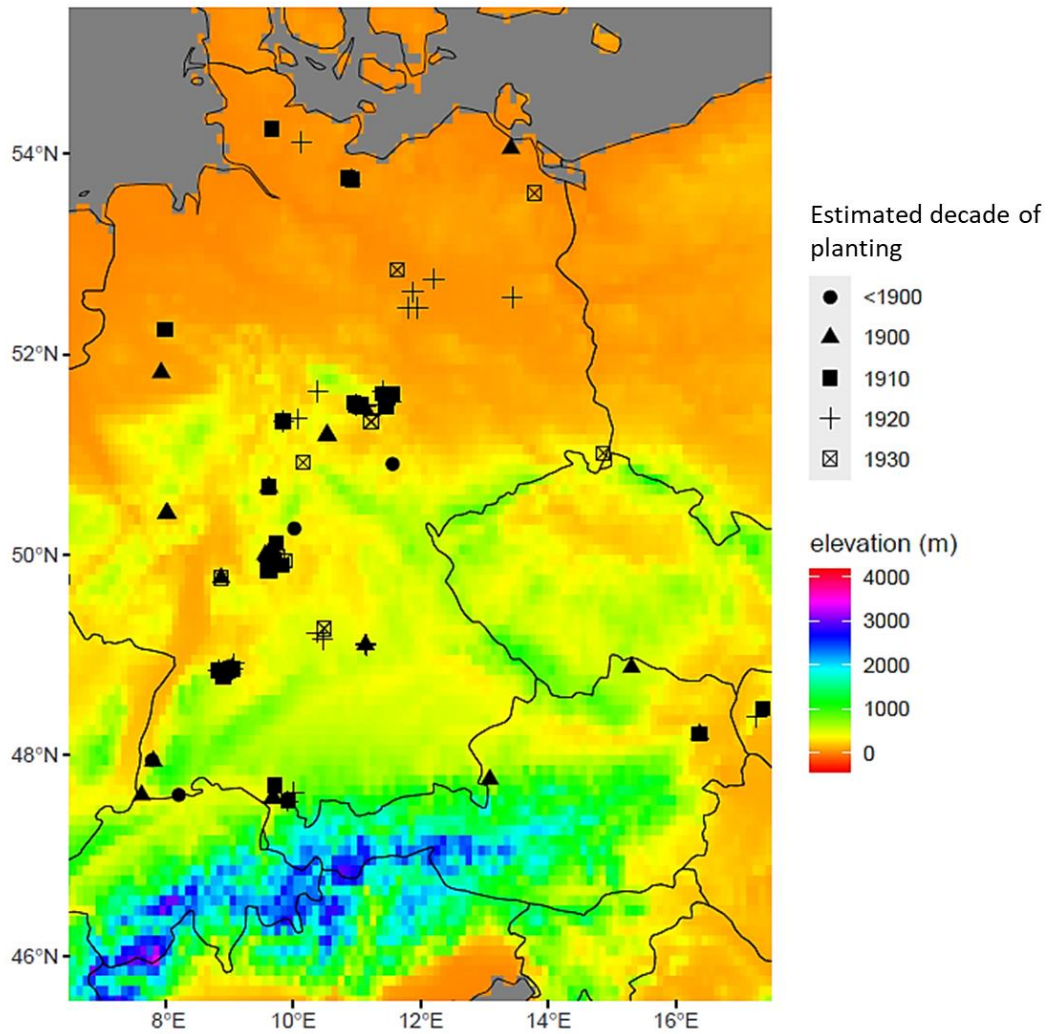

Figure 5: Map of veteran apple trees assessed by participants

Shapes are distinguishing the estimated age of the trees, as estimated by citizen scientists based on expertise, local knowledge or archived information. Background colour was realized with European elevation grid data.

Figure 6 below displays the BBCH code and local phenological season for all 148 trees that participants hat provided both variables for. BBCH codes are displayed as boxplots with medians, three trees representing outliers can be seen in spring3 (late spring), one in early summer and three in summer season.

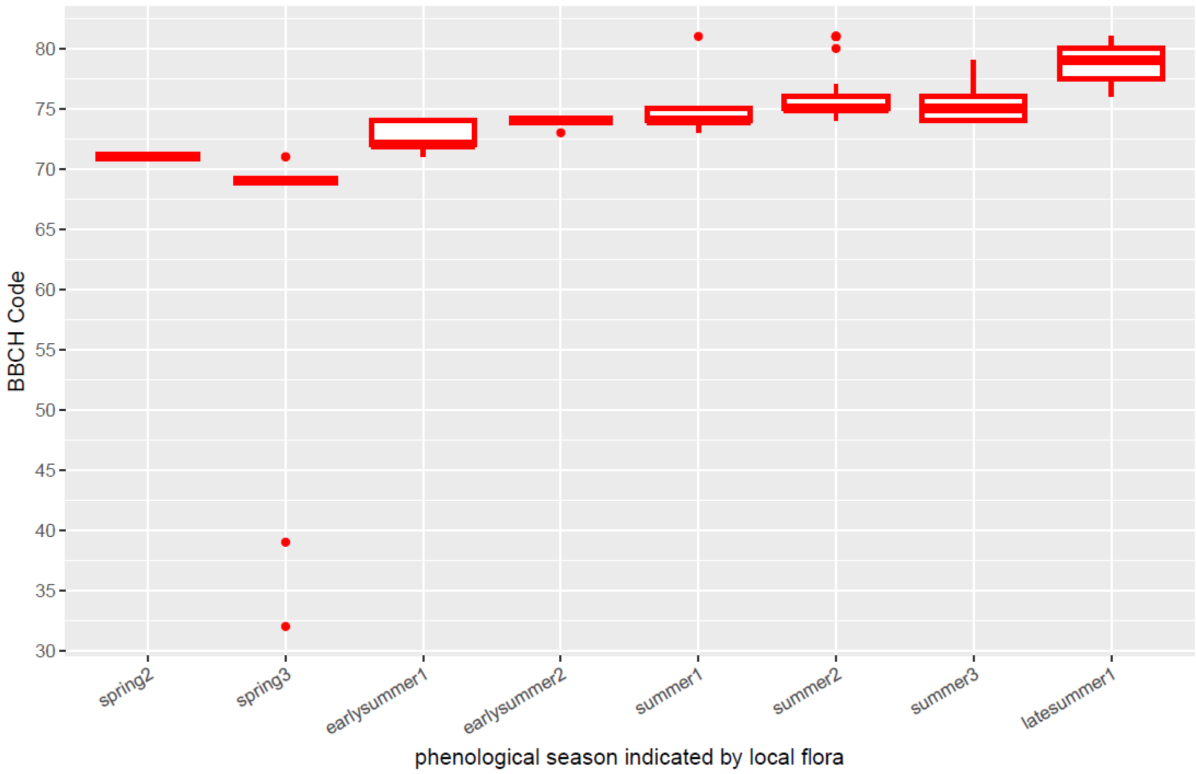

Figure 6: BBCH codes of 148 of the assessed trees in relation to the phenological season

Both according to participants that were utilizing guidelines to determine BBCH code and phenological season locally. Incomplete datasets were removed.

Figure 7 below displays exposure of trees in three levels (sheltered to exposed), as related to observations of flower frost events at any point in the past and relative time of flowering compared to other trees nearby, if there were trees nearby. Most trees were described to flower neither early nor late, but intermediate. Most trees out of this group were also described as growing sheltered. Trees described as flowering early were mostly growing in sheltered conditions. Relatively late flowering trees were found in all three levels of exposure, one tree was described as flowering very late and being exposed. Flower frost events were observed at trees with any relative flowertime except for one tree that was described to flower very late.

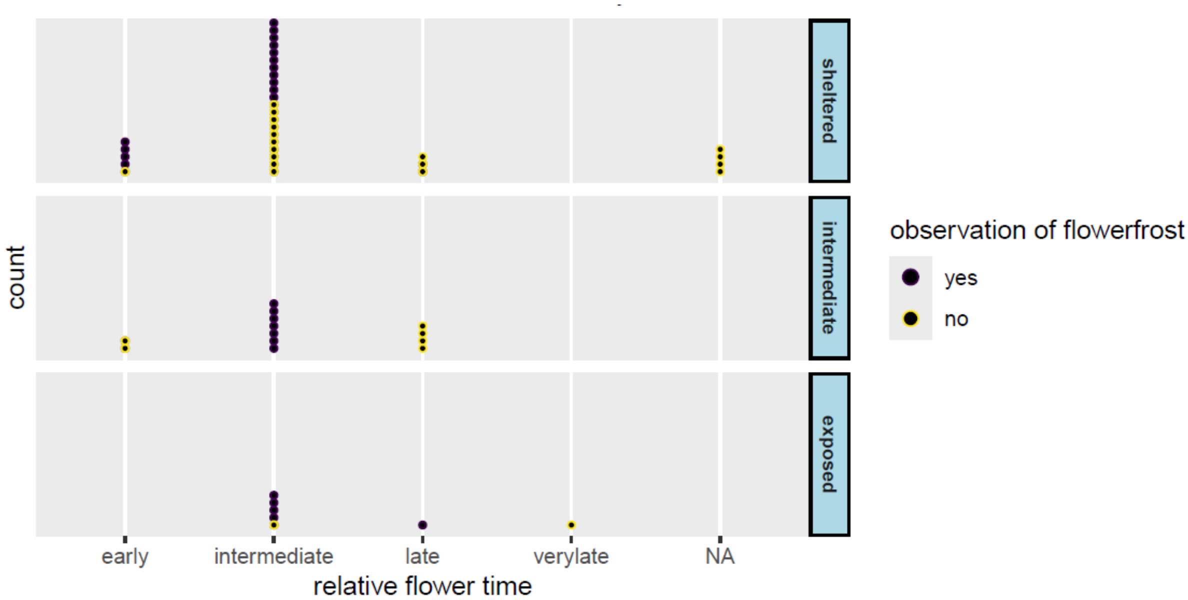

Figure 7 Observations and reports of flower frost (at any point in the past) by relative flowering time and local exposure

n = 70 trees that participants provided the voluntary variables “exposure” and “observation of flower frost” for. Relative flower time was estimated by citizen scientists in comparison to other apple trees nearby, exposure was estimated based on the advanced participants experience.

Figure 8 below displays shoot growth of 152 trees, that were described by participants in 4 levels from "none" (no or nearly no fresh shoots that emerged in the current year) to "strong" (strong growth of new shoots that emerged in the current year). Shoot growth is displayed in relation to 75-year mean annual rainfall, that was calculated via daily rain sum data for each tree's location. Trees with every level of shoot growth were reported, few of them with nearly no shoot growth remaining, the majority of trees were described to have medium or strong shoot growth. Mean annual rainfall of the tree's locations ranged from less than 500 mm to slightly more than 1800 mm of rain per year.

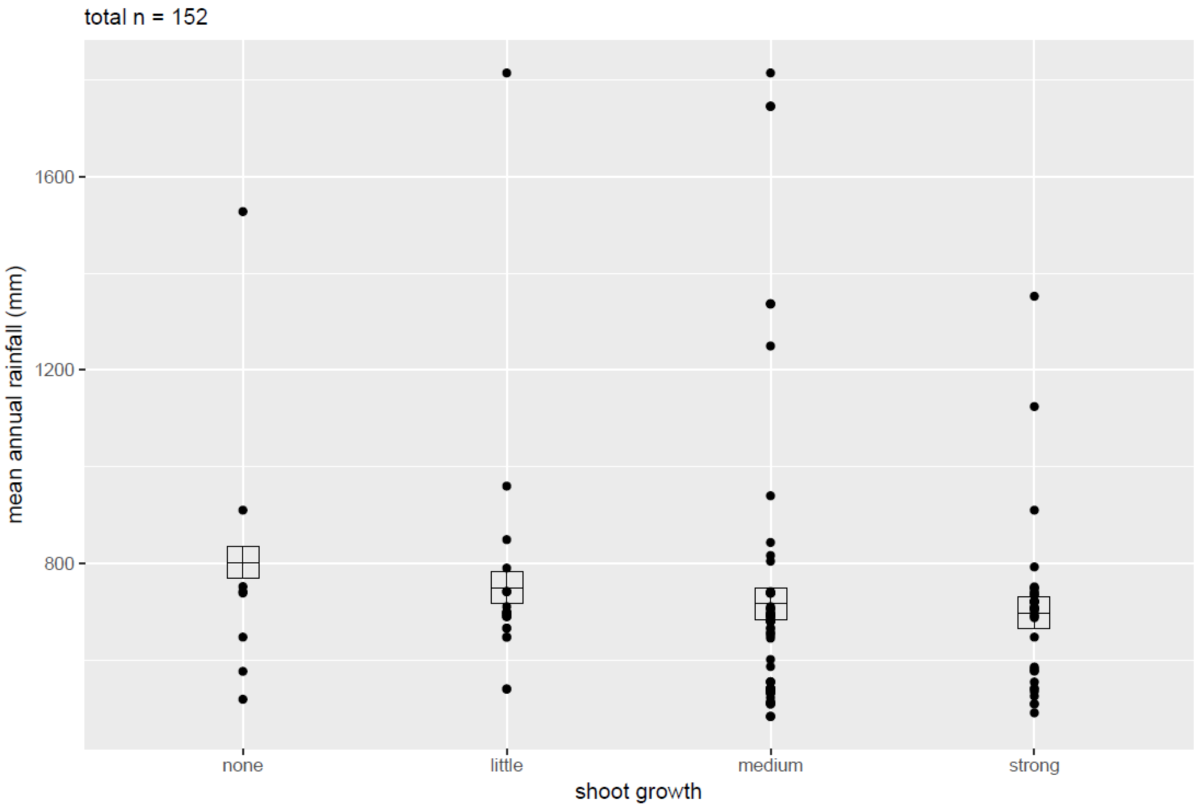

Figure 8: Vegetative shoot growth and 75 -year-mean annual rainfall of 152 trees

Incomplete data sets were removed. Shoot growth grading in classes from "none" to "srong" was based on the participants experience.

Figure 9 below displays three leaf characteristics: thickness in three levels, presence of leaf trichomes in three levels and cuticula thickness in two levels: being extraordinarily thick and visible or not. Only leaves of rootstocks, meaning sucker leaves or leaves of not grafted trees, were observed, mature leaves from long shoots were asked to be favoured for this observation. Sun exposure was translated into a numerous factor from participants inputs on light or deep shade that was shading the tree from different cardinal directions. Local water retention index was added to the data set via grid data and the trees coordinates, representing a range of factors, that are impacting the retention of water in the area. Many trees that leaf data is available for were exposed to nearly full sun or full sun, while none of them was growing in full shade; water retention for these trees ranged from 1.3 to 6.3 approximately. Leaf characteristics were diversely scattered on the matrix.

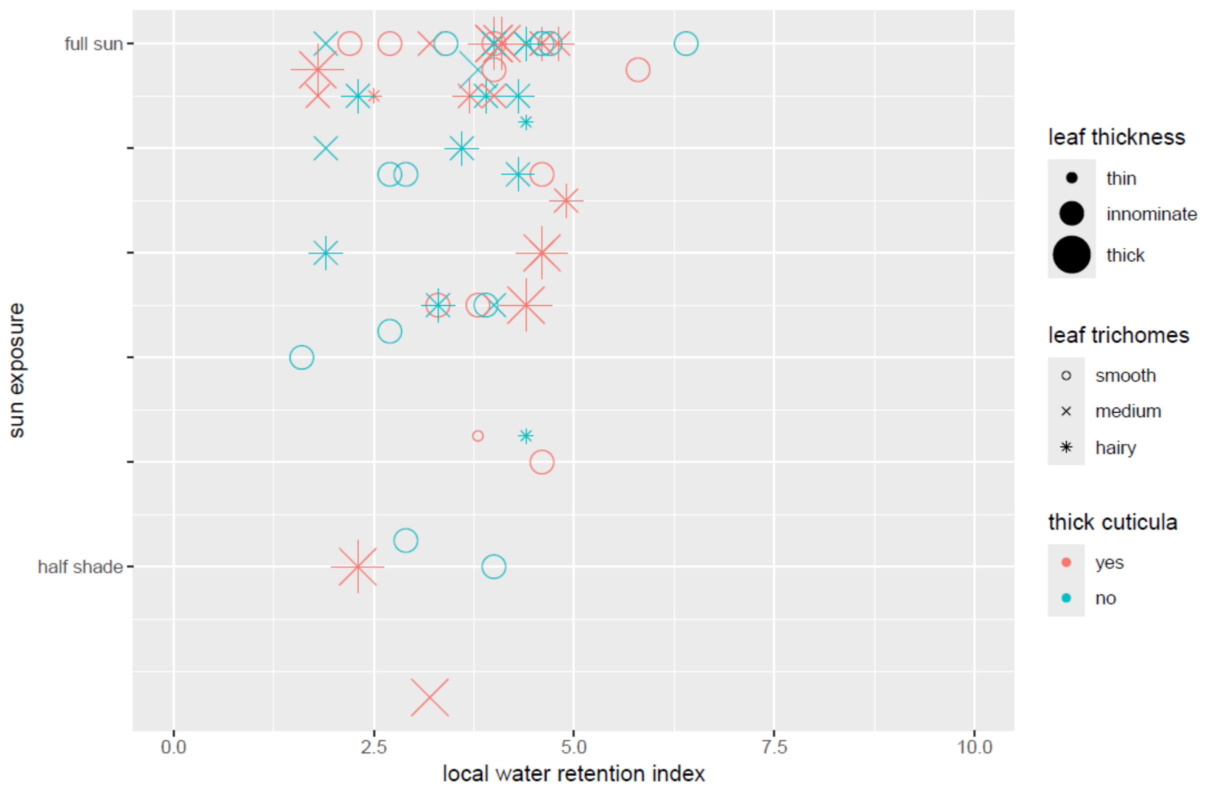

Figure 9: Leaf characteristics as observed at rootstock (root suckers emerging from rootstocks or supposably not grafted trees as observed by citizen scientists), displayed on a matrix of sun exposure level and local water retention index

Incomplete data sets were removed. Sun exposure was queried for cardinal directions, four intercardinal directions and in two levels (light shade; deep shade) and systematically translated into numeric values. Leaf characteristics where described by sampling several leaves and observing without technical support. Local water retention index was added by grid data. The whole dataset is displayed, the ordinate was restricted for aesthetic reasons.

Figure 10 below displays the total stem circumference, meaning the circumference of trees with one stem and the cumulative circumference of multi stem trees. Crown volume was estimated as a cone using data of crown diameter, tree height and stem length. Water retention index of the trees locations ranged from 1.3 to 6.7 approximately. Calculated crown volume was less than 375 m³ for most trees, but three outliers were calculated to have crowns with volumes more than 750 m³. Stem circumferences were ranging from less than 100 cm to more than 300 cm, with most observations stating values between 100 and 200 cm (histogram not shown). Different combinations of stem circumference and crown volume were present at varying levels of local water retention. and no apparent linkage between these two could be stated.

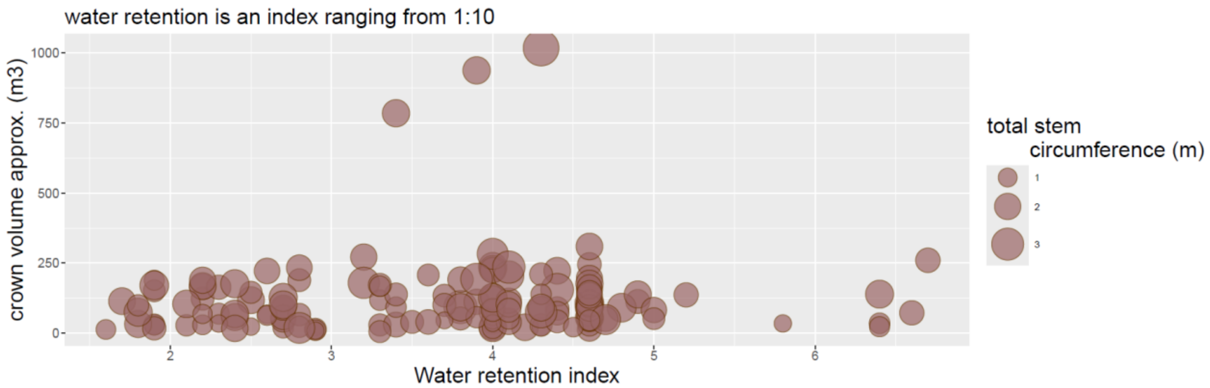

Figure 10: Crown volume and stem circumference (data for calculation measured by citizen scientists oriented at standardized protocols) in relation to local water retention index, that was added via grid data

n = 154

Figure 11 below displays what extreme events were experienced by the trees in the past, an information that was provided by the participants themselves or local people they were able to ask about it. Nearly 75 trees were reported to have witnessed extreme drought events, but less than 10 trees had seen extreme waterlogging conditions. More than 50 trees were stated to have experienced historically outstanding winter frost periods, but extreme spring frost events were mentioned by nearly no observer.

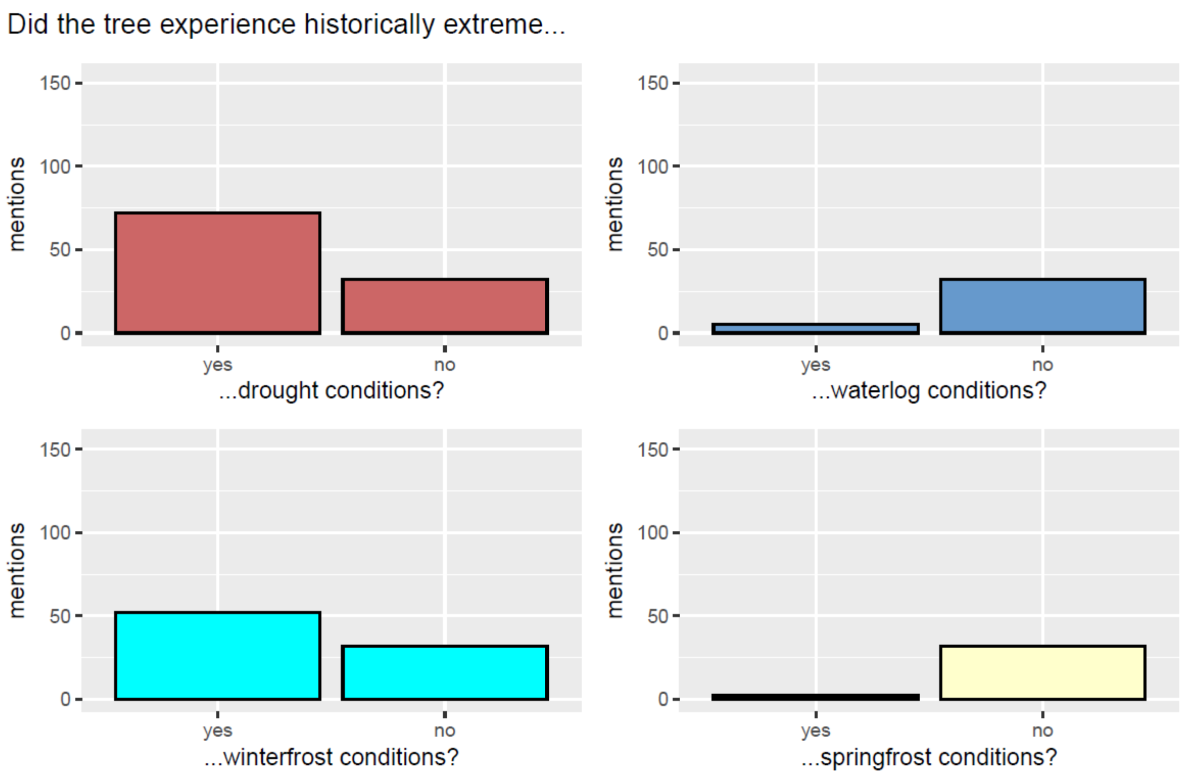

Figure 11: Historical extreme weather events experienced by the trees, as stated by long term observers or local people

Winterfrost and springfrost events were mentioned in free text boxes only and not a multiple choice option.

Figure 12 below displays grafting, grafting position and potential means of propagation of all assessed trees. More than 75 trees were described as not being grafted. Grafted trees were mostly visibly grafted in low positions, only. Not grafted trees, grafted trees with suckers and grafted trees with suckers that were flowering or fruiting were interpreted as being propagated vegetatively and generatively, respectively.

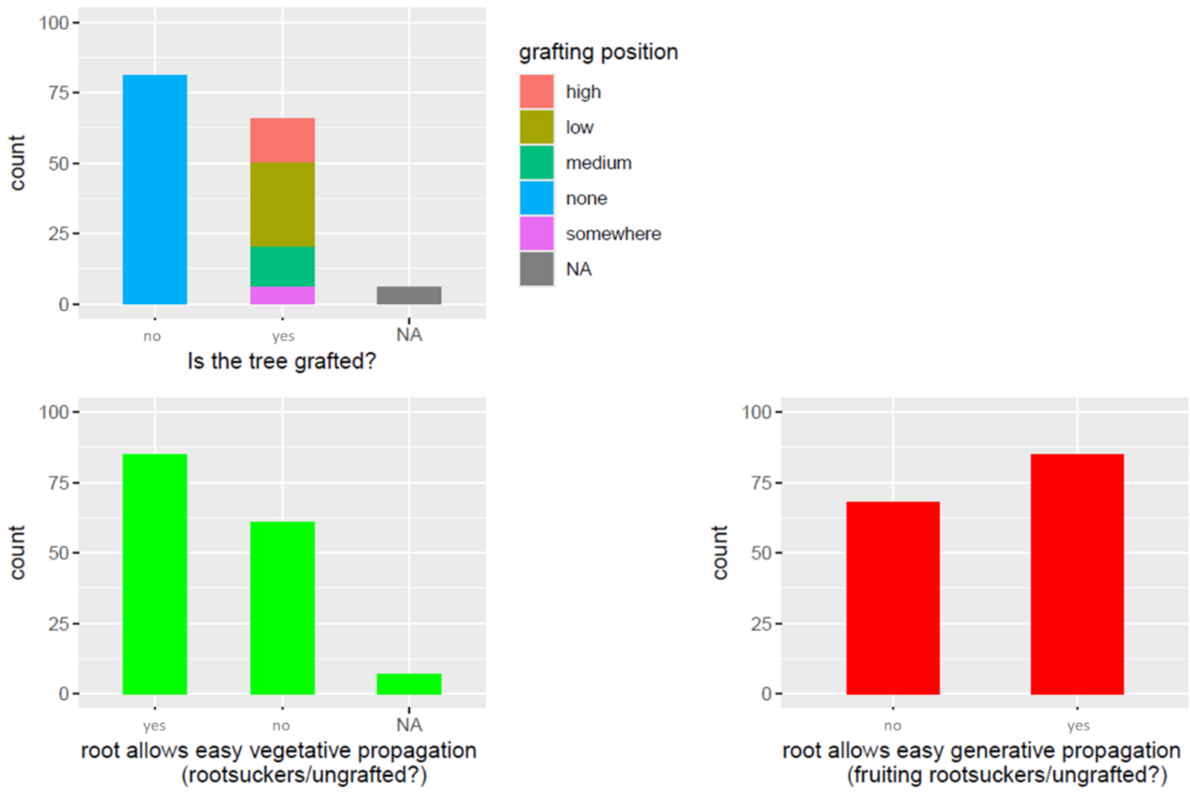

Figure 12: Grafting and potential means of propagation of assessed rootstocks

4. Discussion

4.1 Interpretation of results

Discussion of literature work

Recalling the questions that were aimed to be answered in the literature work of the present project and thesis:

What requirements are imposed on rootstocks for vigorous, standard sized apple trees?

Requirements imposed on apple rootstocks are reflecting the various interests and environmental conditions, that apple trees are linked to. The goal was, to list requirements imposed by established and future conditions to identify traits of interest that could potentially be observed by citizen scientists. When reviewing the literature, this initial idea was constrained by different limitations:

Transferring objectives of conventional rootstock breeding to objectives for future vigorous rootstocks is obviously not possible in many cases, when growing conditions of apple trees in alleys, *Streuobst* meadows and agroforestry systems are considered:

Imparting of dwarfism, precocity and sylleptic branching are the most obvious traits, that are not compatible or even obstructive to the intentions of growing vigorous apple trees.

But even when excluding not suitable or less pressing requirements, the remaining requirements that were collected often appeared contradicting or adverse.

So are the forecasts of future climate conditions for Germany and their neighbouring countries, that will be very differentiated on the regional level. And additionally, so are the use cases for rootstocks for vigorous apple trees, that can be characterized by different levels of maintenance, production systems, or ecosystem service of interest, for example.

Nevertheless, many requirements listed are pointing in the direction of “robustness”, that is also highlighted by Hanke; Flachowsky 2017, when calling for systemic innovation in fruit crop breeding.

Implementing the traits of interest in an exhaustive assessment protocol appeared challenging, as the mere plurality and large number of interesting traits was requiring experience, time and even local knowledge to succeed. Additionally, the observation of the rootstock is difficult due to it's obscure growing position or it's indirect trait expression via the scion growing with it. Knowledge gaps and dependencies linked to apple trees are drawing a picture far more difficult and uncertain than the collection of favourable, but achievable traits of apple rootstocks does evoke:

Soil quality and microbiome are impacted by climate change, with little knowledge yet existing on the actual effects and consequences of this impact (Jansson; Hofmockel 2020). Soil characteristics are at the same time a factor of great importance when discussing growing conditions of apple (Korban 2021), thereby representing a very complex and nearly unpredictable requirement that rootstocks will be confronted with.

Puglielli et al. envisioned a virtual special Issue "on woody plant adaption to multiple abiotic stressors" in 2023. The main outcome of that issue was the acknowledgement of many gaps, that still need to be filled to understand woody plant's adaption to upcoming abiotic stressors: Availability of data and the unifying of frameworks to explain woody plants behaviour were existing challenges, not allowing to identify patterns and mechanisms. Thereby, woody plants, and apples, reaction on future scenarios with diverse abiotic and biotic stressors remains unclear. Tian et al. 2023 were modelling the impact of future climate change on woody plants habitats of China, just as kajtna et al. 2023 did for Austria. Both concluded, that a spatial shift of suitable areas to grow certain woody species is laying ahead. Adaption by a foresighted decision based on the latest knowledge available when making choices on growing regions and sites should be considered as well, alongside with improvements of plants. This fact is even more obvious, when not only changing means, but extreme events are taken into account: Ruess was summarizing potential negative and positive impacts on fruit production in the Neckar-region in 2020. They described an increased risk for damage by hail and thunderstorm with heavy rain, especially in regions close to mountain sites that are promoting precipitation. This trend is also anticipated by Brasseur et al. 2023 for different regions of Germany.

Additionally, limitations of the presented collection of requirements are obvious, when the simplified view focussing on the tree only is discarded and its dependency within the (agro)ecological system is recognized: For example, Climate change might lead to spatial mismatches between apple crops and their wild bee pollinators, when their phenological reaction on a changed environment is not synchronized. Problems with pollination in apple orchards could be a result, as wild bees are an important addition to commercially used honey bees, due to their robustness (Marshall et al. 2023).

Wyver et al. 2023 concluded from analysing phenological trends of apples and their pollinators, that mismatches are possible, but dependant on small scale regional circumstances.

The examples above are aiming to contextualize the requirements listed for future vigorous climate resilient apple rootstocks to emphasise the fact, that development and breeding of rootstocks is only one part of the adaption, that is needed to heave standard sized apple trees in a climate change future. Not all requirements for future vigorous rootstocks can be addressed with the present approach, thereby, requirements concerning interspecific ecological linkages, future border conditions of the economic systems or social developments were not listed in this section.

Eventually, many traits of apples that were simply not observable by citizen scientists were aimed to be excluded from the literature review from the start. This was mainly true for traits that could only be observed with technical support (for example leaf architecture, underground root architecture).

What potentials for future breeding projects could potentially be embodied by veteran apple trees?
Success in breeding is dependent on variability and the presence of favourable traits. The first step of breeding processes, allocating the initial variability, is described as the probably most important step to impact the success of selection by Becker 2019a. Drawing on a well-established and developed pool of variety is thereby considered to assure breeding success in the long run, instead of short term, short living improvements based on an insufficient selection of parent material (Becker 2019b; Becker 2019a).

Taken into account what is known about the history of rootstock utilization and the few examples of research and use addressing similar trees, the potentials for future breeding prospects embodied by veteran apple trees can reasonably be expected to be worth surveying. Based on the recommendation expressed by Denney et al. 2020; Cortés et al. 2020 to realize habitat based assessments, greatest potential could be hidden in trees that ware obviously expressing healthy growth under challenging conditions, meeting the required “robustness”, that was embodied in many requirements for future vigorous rootstocks, that were discussed before.

Due to their obscure ancestry, no specific potentials can be concluded. The outstanding longevity of veteran apples, partly under challenging conditions, is solely proving their ability to support a robust tree under the specific growing conditions that are present in its habitat. Evident potentials can only be the subject of future studies concerning accessions of veteran trees.

What citizen science could be utilized to collect valuable data on veteran fruit trees?

Tools of citizen science suitable to collect data on veteran apple trees were easily retrieved from the literature.

The presence and active engagement of the German association on pomology and associated groups like tree wardens and tree workers, was an important foundation to decide on the level of participation. As higher levels are requiring more experience and/or training, the chosen level was relying on the contributions of these specific target group and its network connections. To not rely on this networks’ abilities exclusively and to try to discover trees, that are not known by this expert group already, advertisement was spread in other networks, citizen science platform “mitforschen!” and via press releases as well, as described in the methodologies section. Anyway, the complexity of the assessment protocol, that was linked to a specific effort and required some expertise in the field, was not adapted to this extended target group, as it was expected, that project descriptions included in the registration form would inform potential participants about the complexity of the topic. The result of these decisions can be discussed alongside the data output of the citizen science project.

Also, difficulties were imposed by the differentiation between short and longer term perspectives on the project, when the level of participation was considered. As the present thesis is chained to a specific and comparably short time span, the project is likely to proceed beyond this time span. In this term, the level of participation is likely to vary.

Ongoing engagement of voluntary, scientifically informed activists is what will be needed to tackle the challenge of gathering genetic resources from veteran apple trees, keep data accessible and up-to-date to be used by those working towards climate resilient rootstocks for standard sized apple trees, despite the comparably low economic interest in these rootstocks use cases (Ritthaler 24.08.2024). To set the course for a development in that direction, incentives for networking and collaboration were already included in the present project, thereby going beyond the goals that were set for the present thesis alone.

Phillips et al. where reviewing the potential of citizen science to close the so called “knowledge-to-action-gap” in 2021. They highlighted, that involvement of citizen scientists in issues that is relevant for them and the public, there is potential to raise motivation in participants to take further action at their behalf. The evolution of methodology from simple participation towards “Natural science projects currently being classified as *activist approaches*” (Vohland et al. 2021, p. 90) is opening research projects to be the ignition of ongoing engagement.

Although it appears as if all tools needed were accessible via the reviewed literature, limitations of the created approach can be discussed referring to the data output of the project:

Discussion of the citizen science project and resulting data

Recalling the research goals, the discussion of the data is widely limited to data quality, as solely description, but no concluding interpretation of the data itself was aimed for in this project. Thereby, only descriptive, or explorative statistics, and no statistical analysis or testing of hypothesises was conducted. Instead, it will be discussed if data collection as one goal of the citizen science project was successful, if the provided data is of sufficient quality and interests of the volunteering citizen scientists were met as well. In many cases, interesting aspects worth of further investigation will be pointed out.

The assessment protocol for veteran apple trees was derived from the requirements for future vigorous apple trees presented in the results section. Some limitations applied, additionally to those already mentioned when discussing the requirements themselves. Some traits of interest could not be translated in questions suitable for a citizen science project. Identified reasons are listed in **table** 11 below.

Table 11: Reasons for excluding traits of interest from assessment protocol

Not suitable for assessment protocol: reasoning	Examples
Not observable (time constraints or time dependency of the trait)	Phenology throughout the year
Exceeding the experience expectable for citizen scientists	Recognizing and differentiating different diseases
Not observable without extensive studies, technique, or replication	Accurate age, Sensitivities to a wide variety of disease; reproductivity; microenvironmental conditions; root architecture; root growth characteristics; water relations; chilling requirement; grafting compatibility

Emphasising the impact of microclimates, that was stressed by (Denney et al. 2020) questions were focussing on observations that were very local and could not easily be represented by grid data.

Strengths and limitations of the assessment protocol will be discussed alongside with the resulting data.

Addressing the needs of voluntary citizen scientists is inevitable when aiming for effective data collection and sufficient data quality to eventually meet the researchers needs. A project paying attention to participants needs can be evaluated by counts of participants and contributions, for example. Recalling **figure** 1, 2, and 3 displaying the registration of more than 200 interested persons, distributed in different German regions and beyond, it appears like advertisement reached many potential participants successfully. In comparison, **figure** 4 and **figure** 5 are revealing, that only a minor share of all registered persons eventually contributed trees or were enabled by the project layout, to contribute trees – resulting in assessments clustered in few regions. Also, a relevant amound of emails and phone calls were received by the researchers during the project, naming potentially suitable trees that are still hidden in gardens and agricultural sites. These trees could not be assessed within the layout of the present project, as no pomologist or person with sufficient experience and time was present. Or, putting it the other way around: as no suitable role had been determined for persons of that type. The target group defined for this project didn't appear to be capable of assessing these trees, likely due to time constraints. The persons knowing the trees were not sufficiently experienced or engaged to handle the assessment protocol (or even the application form), although they would probably have liked to contribute something.

A potential interpretation of this outcome is, that a wide group was reached by the recruiting strategy, but only persons with a high level of resources (probably expertise, time, mental capacity to undertake the assessment) were addressed with the remaining layout of the project.

Meaning, that many trees that are not already known by pomologists and their network are likely to be overseen, if pomologists and associated persons are the only target group of such a project. When setting up a similar project or consolidating the present, the definition of two target groups with two levels of participation appears to be an option to solve this problem:

Rather than differentiating target groups by their main interest, to solely adapt advertisement, the differentiation by experience and anticipated engagement should be considered. Firstly, the group with less experience and less will to participate actively, that can be involved by crowd sourcing the coordinates of potential veteran trees and a lowr level set of data, that can be augmented with grid data. Second, a group of advanced persons could be targeted, that is scattered over most of the survey area and interested in contributing by assessing all relevant details of trees, that reported by the first group.

The interests stated by registered and assessing persons displayed in **figure** 4 are distinct. As the option "hobby" was included in the latter assessment protocol, only, its popularity in could explain the distinctness in parts. Shrinking of the presence of "practical use" could also be explained with time constraints: Several practitioners that were reached via phone calls throughout the project were reporting the relevant time stress they had due to agricultural work, mainly haying. Letting tree assessments take place in the early year or winter season would probably have led to more engaged practitioners. The lower level of interest in research could be explained by differing intentions of persons initially registering in the project. When checking in with participants of the initial online workshops, some reported, they were mainly showing up as they were interested in hearing what was done and in the outcome of the project. Here, another group seems to be revealed, that was not targeted, but reached by the recruiting strategy: Persons, potentially interconnected to networks, with suitable expertise and engaging in the addressed topic regularly, that are interested in watching, hearing about the outcome, and communicating, potentially sharing information in both directions. When setting up a similar project or consolidating the present, a group like that could be specifically targeted for ongoing advertisement or to facilitate opportunities for events or appointments with local press that can help promoting a project.

The feedback questionnaire that was briefly described in the results section is supporting the statements made above and adding some more important elements to the discussion: the length of the assessment protocol. Although only one person commended, that the length of the protocol itself was problematic, many others did not assess trees, because they could not make the time. Meaning, that a shorter, less time consuming protocol would probably have led to more submissions. Grading with grade 6 could be contextualized with other inputs by the same anonymous persons: Some had not received emails or had overseen them, some stated solely positive remarks despite grade 6, making a misunderstanding of the grading order very likely – a problem that can be solved by a more explicit prompt in the feedback form. Technical issures are difficult to be avoided, but could be addressed by openly displaying a phone number on the projects website and inviting potential participants to call if they would like to contribute, but are not informed for any reason. Data safety was not a prominent obstacle in the feedback questionnaire.
As the vast majority of those filling out the feedback form was responding very positive, benefited from the project and is willing to go on participating, addressing the participants needs could be interpreted as being successful – but final remarks are not possible yet, as a reminder for the feedback form hast not been sent yet and only a quarter of the registered persons have responded yet.

Nevertheless, the citizen science project led to the assessment of 154 trees and 154 sets of data describing observable traits that could be linked to requirements imposed on future climate resilient vigorous apple rootstocks. Reviewing the data processed into graphics, a wide variety of trait observations appears obvious, with some outstanding individuals showing traits that could point out a high potential genetic that is – in interaction with environment and scion, supporting their specific phenotype.

Visibly in **figure** 5, Some trees were assessed in altitudes around 1000 m, some at altitudes close to sea level.
Higher altitudes are linked to lower air temperatures, lower humidity, specific soil properties and over all limitation of plant growth. Due to rain shadows and slopes of the terrain, their growing conditions can be additionally challenging. Also, water tends to drain downslope (Smith; Smith 2012). Thereby trees in low altitudes are more likely to witness water logging conditions. Some aspects of the veteran trees growing conditions were indirectly targeted by questions 24, 26, 30 and 31 (sun exposure, micro topography, local conditions favouring drought stress or waterlogging conditions) of the assessment protocol and the added water retention index and mean annual rainfall are providing additional information to describe the "traits of interest": drought tolerance, waterlogging tolerance, tolerance for harsh temperatures and sun exposure, that seems to be expressed by some individuals. Filtering the data for rootstocks that supporting successful growth under these conditions of multiple abiotic stress could suggest trees that are most interesting for further surveying – allowing to decide upon accession candidates supported by both, small and big scale data (Denney et al. 2020; Cortés; López-Hernández 2021).
Data quality is potentially impacted by participants ability to correctly use the location widget implemented in the assessment protocol or find their location on a map and is thereby difficult to be estimated.

Figure 6 was aiming to depict the trees different of phenological responses to phenological seasons, that allowing a comparison between places independently of their phenological proceeding throughout the year (Kaspar et al. 2015) The root itself is expressing a phenological response and the observable tree is the outcome of it's interaction with the scion and it's own phenological response (Miele 2019; Durner; Goffreda 1992; Radville et al. 2016; Sabbatini; Howell 2013). Individual plant development that is delayed or premature in comparison to most other plants growing under conditions of the same phenological season were expected to potentially embody the trait of interest "phenological adaption", that was formulated according to the literature review.

The BBCH code's median is increasing with proceeding phenological seasons, but no significance can be stated without statistical analysis.

Trees that are relevantly differing from the median could be interesting candidates, with comparably fast, early, late or delayed development, potentially helping to avoid abiotic stresses like late frost events or droughts during summer time.

Regarding data quality: Phenological seasons are indicated by indicator plants and monitoring normally is following a precise protocol, carried out by trained and experienced volunteers and proved by standardized calculations (Kaspar et al. 2015). It can be expected, that participants in the present project were not delivering data as reliable, as volunteers working for the German weather service would – even with support provided by a list of indicator plants and literature recommendations. Retrieving phenological data, from observations documented by the German weather service could be an option to increase data quality. On the other hand, phenological proceeding can differ on the small scale (Denney et al. 2020; Smith; Smith 2012), also limiting the explanatory power of data interpolated from the German phenological observation network.

Figure 7 is displaying observations of flower frost. Rootstocks are potentially influencing both: tolerance of the inflorescences tolerance for unfavourable climate conditions (Zebro; Heo 2024) and spring phenology as stated earlier. As tolerance for spring frost is an identified trait of interest, later flowering phenology and early, but frost tolerant ones are potential candidates for further investigations. As flowering time and exposure to chilling conditions can be altered by the microclimate provided by the individual surrounding, the exposure of the tree was included.

Though the option "I don' know" was provided, participants could still have chosen "no" mistakenly, if they had simply never observed flower frost because they did never visit the tree in the times of the year. Also, the description of the site's exposure in three levels, that are allowing and requiring a lot of subjective judgement, were strongly relying on the expertise of the targeted advanced participants, though were also supported by examples for each level. Even the third data input visible in this **figure** – the relative flowering time - is obviously drawing from pomologists expertise and relying on their ability to reflect on the question, if they can really provide meaningful information. To support this reflection, the descriptive text of the question was explicitly prompting to try and think from an objective perspective and to not answer, if there are simply no trees nearby, the individual could be compared to.

Figure 8 was relating the shoot growth as an indicator for vitality, a practice described by Heidenreich et al. 2024; Wulff 2023, to the mean annual rainfall added to the tree's coordinates. Many trees were described to realize medium or strong growth of shoots, even when growing with less precipitation per year than the nationwide mean of about 700 to 800 mms (Umweltbundesamt 16/09/2025). No clear linkage from mean annual rainfall to shoot growth appears to be obvious. Instead, sustained vitality, at least indicated by shoot growth, seems to be possible in environments ranging between less than 500 to more than 1600 mm of rain per year. An interesting factor in this contest was explicitly included in the assessment protocol: maintenance by pruning. Filtering the datasets by shoot growth, interestingly, various states of maintenance are reported (data not shown, cf. raw data in digital **appendix** 13). Additionally, strong shoot growth was observed on sites with water retention indexes ranging between 1.7 – 6.6 (data not shown, cf. raw data in digital **appendix** 13), indicating, that even supporting factors like a strong water holding capacity and dedicated maintenance were not the factors leading to the observed vitality. Especially these individuals growing under extreme wet or dry conditions could be subjected by further investications.
Regarding data quality, estimating tree vitality by annual shoot growth is common practice for pomologists (cf Grolm 14/11/2024; Kletterblatt 2011) and is easiily observed. Inputs on trees with very inhomogeneous growth were asked to be "levelled out" – meaning that a tree with a strong and a weak part would become an intermediate tree. The assessment protocol did not provide an orientation to decide how many centimeters of fresh growth are weak, intermediate, or strong growth, probably limiting the reliability of the data. Persons with not confidence as usually had the chance to state that they could not provide this information.

Figure 9 was showing leaf characteristics, that are controlling leaf transpiration and are thereby associated with drought tolerance: leaf thickness, trichomes and markedness of the cutilcular wax layer (Zahedi et al. 2025; Brito et al. 2025). It was considered being interesting to prove, if trees expressing these traits would be found especially at sites that are prone to water scarcity. Hence, their relation to sun exposure and local water retention was explored.
But: All combinations of traits were observed in leaves at varying levels of sun exposure and water retention and no apparent linkage between these two environmental factors and leaf characteristics could be stated. Anyway, not all factors influencing the need of a tree to reduce transpiration are included in the plot and patterns could still be found with further data analysis, supporting potential selection of candidates that could be well adapted to water scarcity.

Regarding data quality: Only leaves of not grafted trees or roots suckers were sampled, which was assured by a filtering mechanism implemented into the assessment protocol, hiding these questions for those that stated a visible grafting but no suckering.
Unfortunately, the data quality could be constrained by difficulties in sampling: representative sampling is only possible with some effort and corners could potentially have been cut especially when in the field without a ladder or telescope clippers.

Another property of the leaves was observed: leaf size, a simplified version of the leaf area, that is often associated with drought coping mechanisms as well (Greenwood et al. 2017). Anyway, leaf size in centimeters was not included in the exploration of the data, as the size can vary over the whole tree, is depending on a large range of different factors (Tabeta et al. 2023).

Figure 10 was exploring the relation of total stem circumference, crown volume, and local water retention index. A slim stem was identified as a potentially favourable trait, as slim stems and dense wood could be more successful in avoiding hydraulic failure (McGregor et al. 2021; Greenwood et al. 2017). Anyway, different combinations of stem circumference and crown volume were present at varying levels of local water retention and no apparent linkage between these two could be stated without further investigation. Various tree proportions are indicating, that water retention of the soil is not the only factor having influence. Multi factor analysis including annual rainfall or rainfall during vegetation phase could be included just as other factors influencing dry matter consolidation, could be observed, eventually filtering out the leftover effect that is probably induced by the rootstocks and scions genetic. As the dataset that is already available doe to the present work is already including many of the potentially relevant factors, filtering could point out candidates for further investigations.
Regarding data quality: measuring the circumference of the stem or stems was an easy task, that is not prone to fail. But crown volume on the other hand was calculated by stem length (≈lower border of the crown) and total tree height, that was estimated utilizing a supportive guideline explaining the intercept theorem. The intercept theorem is prone to fail, when it is not carried out correctly and not critically questioned with a reality check. Although the guideline was naming the important obstacles that could lead to wrong results, it’s currently unclear how challenging or easy this task was for particpants. The calculation of the crown volume was using a cone shape for rough approximation, oriented by Höller et al. 2021 estimating small crowned trees, a shape that might fail to describe some crowns with extraordinary shapes.

Figure 11 is describing the prevalence of extreme weather events witnessed by the assessed apple trees and their rootstocks. As part of the assessment protocol, it was prompting participants to write down what they knew or could investigate by talking to old locals or local (hobby) historians. The question was integrated to check upon the assumption, that veteran trees are not only growing under very lucky conditions and were spared by extreme events. Those are referred to as "negative signature years" by (Schwärzel 2000) and that are often leaving a trace in the development of a tree that can be investigated with dendrochronological means – or alternatively causing the die-off of the tree. According to the participants, the trees survived several extreme weather events as described.
Regarding data quality, the question was specifically aiming for events in the distant past and separating this question one that was asking for extreme conditions appeared more contemporarily and thereby likely influenced by climate change conditions. A complementary question was asking for a short description and year of the extreme event, assuring, that inputs were fair. Unfortunately, incomplete suggestions were made in this question, asking for drought, waterlogging or "something else, for example extreme cold" that could be stated in the free text field as well. It is expectable, that participants were more likely to recall droughts and floods than cold winters or even extreme late frost events, that were not mentioned explicitly.

Figure 12 was created to inform researchers and practitioners that are interested in surveying or propagating trees that are showing promising or interesting traits. As many trees were described as probably being not grafted, a direct vegetative propagation could be possible for these. To be precise, vegetative propagation of not suckering, grafting trees is possible as well and was experimentally surveyed by (Feuerhahn 2000), already. While propagation via root cuttings and in vitro culture is more time consuming, sensitive and requiring equipment and expertise, reproduction of apple via cuttings, though not easy in comparison with other woody plants cuttings (Singh et al. 2019; Osterc 21.2.2000; Wang et al. 2024a) can usually be realized with equipment that is available in most woody plants nurseries or easily available.
Depending on the presence and diversity of other apple trees that could be involved in the rootstocks pollination or by controlled hand-fertilizing with a suitable second parent, generative propagation could be an option as well, to directly produce an offspring generation to be selected from. Further considerations on potential future research involving the assed veteran trees are described in the research perspective.

Regarding data quality, limitations are easily visible: Not visibly grafted trees are not necessarily not grafted seedlings or rooted cultivars. They are potentially grafted very low or the grafting is not visible anymore due to the thick formation of the trees' bark. Especially if the visible scion can be identified as a known cultivar, its more likely that the tree is grafted or was grafted once, for cultivar propagation. Anyway, disengagement of scion and rootstock is possible, when the scion is getting in contact to the soil for any reason (Büchele 2018). Therefore, comparison of the genetic identity above ground and the root is inevitable to verify the information provided in the present dataset.

Data management as defined by Fraisl et al. 2022 is including description, preservation, and integration, summarized as "assuring future data usability" in the present project.

Descriptive data visualisation was aiming to give interested researchers an overview of the diversity, limitations, and potential uses of the dataset. Not all traits that are accessible in the raw data set are displayed due to timely limitations inherent to writing a thesis. To provide a good overview for the researcher of the present project and represent the data appropriately to others, the whole data set was categorized as described in the methodologies section. Arguably, the prevalence of fungal or other diseases would have been an interesting variable to be included in a **figure**, as disease robustness or resistance are an emphasised objective of conventional rootstock breeding and of great importance especially when climate change conditions are causing raising pressure of many plant pests (Augustenberg 2025; Flachowsky; Töpfer 2021; Skendžić et al. 2021; Zhu et al. 2023; Göding 2021; Schneider; Rebetez 2023) It was not chosen to be displayed in a **figure** due to concerns regarding representativity of the data, as the field of phytopathology is very wide and complex, making precise observations difficult even for experts. Additionally, symptoms are often not visible at every time of the year (Poehling; Verreet 2013), limiting the reliability even further, even if the observer is capable of recognizing the symptoms.

Soil characteristics such as soil type and characteristics indicted by indicator plants could have been chosen as well, potentially illuminating the soils impact on the trees vitality. As water relations of the soil were already, and probably more exhaustingly covered by the water retention index and plants indicating nutritious, poor, salty, acidic, basic or dense soils were rarely observed by participants, other data was prioritized.

The data on veteran apple trees and their rootstocks derived in this project has been described and is accessible in the digital **appendix**, but data is mainly raw and requires processing to be understandable and ready to be used by others. A preview on the provision of the data in the future is provided in the section on a research perspective, as it is not covered within scope of this thesis. The success and limitations of the citizen science approach was discussed and recommendations to be integrated in similar projects in the future were made.

4.2 Critique of methodology and limitations of the presented work

Additionally, to discussion alongside with data presentation the following considerations are relevant and concerning the project as a whole:

General Data quality

In the present project, with participants mainly contributing data and little involvement in question design and data management – except for the presentation and exchange on the assessment protocol prior to the data collection phase – data quality needed to be assured by the researchers by implementing suitable means. The preface of the protocol was stating, that only information that participants were sure about should be stated, but no general or specific guidelines on data quality were phrased, whilst being suggested by Bonn et al. 2022. Nevertheless, standardized procedures for several observations were included in the assessment protocol as supportive documents directly visible in the workflow of the protocol. Question design was aiming to avoid unintentional misstatements. Extensive training beyond one practical field workshop unfortunately could not be realized in the present project, due to limitations of time and funding. But reachability of the researcher for participants around the clock in case of difficulties during assessment was offered and delivered. Collecting evidence with photos was not implement to avoid further inflation of the assessment protocol. Targeting advanced participants was integrated in the project layout, making high quality data inputs more likely.

On the other hand, many observations and derived datasets are based on relative observations and the ability of the advanced participants to integrate the local conditions and their expertise in a valid statement (e.g. “relative flowertime” and “climate stress”). The background of each share of data therefore should be interpreted on the foundation of the question it was derived from, to judge the reliability of it accordingly.

Timeframe of data collection

Some information is indicating, that an extended time frame for data collection would have led to more assessments: submissions mainly happened in the last two weeks of the time frame, the feedback form showed that many registered persons would have liked to contribute a tree but could not make the time and summer time is busy for practitioners. An extended time frame or open phase of data collection over a longer time span could yield more assessments in future projects.

Time management and parallelization of data collection and analysing

It is recommended by Fraisl et al. 2022 to plan and operate data analysis parallel to data collection. Presenting previews of the data contributed by the community could raise motivation, would have allowed an extended time frame of data collection and would have been possible by writing R scripts and running them with the submitted data at different points throughout the proceeding project.

Unfortunately, structuring and preparing the data for processing in R was linked to relevant efforts, due to the missing delimiters in data exports derived from *jotform*, the chosen software for data collection. Hence, preparing large chunks of data at once was time effective, resulting in only two data exports: A month prior to and right after conclusion of data collection. This strategy was applied to avoid time stress. The obstacle could be side stepped by using different software for data collection. Tools that are specifically designed for citizen science projects, like "spotteron"[15], are providing an included data visualization that is accessible for participants as well, but exceeding the financial resources allocated to the present project.

Question design

Question design was not always optimal: The question design of the assessment protocol was aiming to maximize convenience and assure data quality by providing understandable options as text. Due to the difficulties in data export mentioned above (missing delimiters to differentiate multiple choice answers), separation of the different character strings was additionally time costly. Retrospectively, the difficulties in data export could have been revealed with the testing of the assessment protocol and led to appropriate adjustments, but unfortunately was not noticed. Adding a delimiter to each multiple-choice option in the protocol itself would have been a quick and easy solution to the problem. In one case, a question aiming for numeric values (leaf size) was prompted with a range description as text, that had to be retranslated in numbers by the researcher afterwards – instead, offering numbers

[15] https://www.spotteron.net/de/

as options and asking participants to calculate a mean from there sample would have been the easier way.

The subsequent addition of an option to be chosen from in the question asking for participants interests ("hobby") was impeding the interpretation of the data output. Although the option was popular for persons assessing trees, a consistent question should be favoured.

Chosen grid data for augmentation of the data set

Other data sets could have been chosen to augment the data set produced by the citizen scientists in the present project. Parent material or "bed rock", the underlying geological material, that are providing the foundation for soil formation (Blum 2012) would have been an interesting factor, but it's impact on the growing side, mainly water percolation, soil formation and soil properties were already covered by the data on water retention and plants indicating soil properties. Additionally, data on parent material is not available in high resolution and the whole of Europe, but only in a 1 x 1 km grid[16] for the whole of Europe or alternatively as datasets of higher resolution, but not harmonized for separate countries (personal communication to a former employee of BGR[17], the German agency on geoscience and primary resources). Top soil properties could have been added utilizing freely available datasets by the European Soil Data Center as well, but would have added redundancy to the more local soil properties already assessed by participants and were thereby prioritized low – they could be a fair option for future low level assessment protocols for participants with little time or little expertise.

Air temperature, heat events, humidity, and soil moisture data is accessible for Germany via the German Weather Service and would have been a good choice to evaluate veteran trees in terms of heat stress and soil water availability, but timely constraints inherent to a thesis did not allow it.

Overall significance of tree data observations

The phenotypic expression of a grafted tree is resulting from rootstock × scion × environment interactions (Albacete *et al.* 2015). Height of grafting, the use of interstems; grafting technique, and the influence of the scion on the rootstock are playing a role as well (Richard P. Marini; Gennaro Fazio 2018, pp. 205–209). Hence, the targeted characteristics could not be observed directly by citizen scientists, but indirectly by observing the whole tree resulting from rootstock x scion x environment interaction.

[16] https://esdac.jrc.ec.europa.eu/content/european-soil-database-v2-raster-library-1kmx1km
[17] https://www.bgr.bund.de/DE/Home/home_node.html

Vice versa, if trees were not grafted, the rootstock as an organism was observed despite the fact, that not its aboveground phenotype, but solely it's function as a rootstock and it's interaction with scions is the main interest of the present work. Data derived from the present project thereby can only provide indications to choose candidates for more extensive surveillance.

Applicability of criteria for veteran tree selection

Criteria for tree selection were: "old age" (≥ 95 years) > "challenging growing conditions" > "vitality" as derived from literature work. While old age was important to make sure to target trees that were grafted on unique rootstocks of unknown genetic identity, because standardized and professionally produced rootstocks were not very common in their decade of planting, determining the age is an obstacle, leading to several questions of participants until the supportive material accessible in **appendix** 5 and 6 was derived and shared in a specified email for all participants. To avoid assessments of trees lacking a fair foundation for their age estimation, participants had to put in a decade of planting, no option "I don't know" was provided and suggestions were made for age estimation. Still, estimations could be wrong due to ill-founded information provided to participants.

Regarding apple tree vitality, no standardized protocol specific for apple trees seems to be available yet, which would have been favourable.

4.3 Research perspective

The final evaluation to allow improvement of future projects, that can be realized posterior to the concluding online meeting and analysis of the feedback form is clearly indicated.

To then conclude the present project, providing the data oriented at the FAIR principles (GO FAIR 21/01/2022) to assure future usability is planned.

The feedback form of the present project was including the request for further engagement, aiming to involve interested persons in a potential participative project of vigorous apple rootstock breeding in Germany; the request was earning many positive responses. Alongside with breeding objectives, strategies of breeding processes can be differentiated as well. Novel strategies are shifting more towards the participation of fruit growers and other stakeholders in the breeding process, including the acknowledgement of genetic resources as commons (Wolter; Hoops 2020).

Promising candidates could be propagated vegetatively, grafted on dwarfing rootstocks to induce precocity and allow premature crossings and progeny for selection in a participative breeding program similar to the tricot approach outlined by Sousa et al. 2024.The project “Trees4Streets” by Kätzel 14.09.2022 is providing another interesting framework to select woody plants towards climate resilience.

Climate resilient crops are meant to tolerate multiple abiotic and biotic stressors, expressing a general “robustness” to assure food safety and farmers economical needs (Kopeć 2024). From a human perspective, one could also talk about the certainty of revenue, which might be food, precious wood or shading and reduction of erosion by wind and water. In breeding theories, certainty of revenue is believed to be higher, when the variance of the plant of interest is higher – linked to a reduction of the mean yield of these more various plants (Becker 2019a). Climate resilience in (agricultural) landscapes is strongly linked to (crop) genetic diversity (Waqar et al. 2024) and diversity can potentially be included as the essential innovative plant breeding objective (Ceccarelli; Grando 2024). Recalling the long list of requirements that were gathered in the results section and the elaborate and time-consuming process of rootstock breeding; rather than trying to incorporate these partly contradicting traits in one or few rootstocks, a strategy of “divide and conquer” could be applied, as it is to the breeding of scions and rootstocks already (Hanke; Flachowsky 2017).

Breeding programs for rootstocks in different places around the globe have adopted regional needs, as apple fruit are produced in the tropical, sub-tropical and temperate zone, and in areas with different levels of specific pathogens pressures. Customized performance for scion variety and production site (“designer rootstocks”, (Fazio 2022)) could be the next step of apple rootstock breeding.

Reasonably, there is a wide variety of conventional, dwarfing rootstocks on the global market as well and their appropriation for the particular use case, scion, growing system and natural conditions is the objective of the consulting that is taking place prior to any profitable planting (Lodder tree nursery, personal communication, 2025). Rootstocks are bred on nearly every continent and geographical regions are often utilizing a set of them to meet their very specific conditions (Richard P. Marini; Gennaro Fazio 2018).

To increase robustness and security for vigorous, standard sized apple trees, conditions are the same and not surprisingly, the need of a range of different rootstocks with adaptions for use under various growing conditions is highlighted (Brüntjen 2019) along with naming susceptibilities that were observed at rootstocks that are currently available. For example, seedlings of the cultivar 'Bittenfelder' are described to be robust and suitable to be adequate to be used on fast-warming, well-draining, yet loamy soils, but to fall short when it is used in windy places - due to a lack of root forming - and wet, cold soils, due to a susceptibility to apple cancer (Brüntjen 2019, pp. 187–189). This call for more diversity is supported by the strategy for climate resilience in agriculture, “Expanding crop genetic diversity” (Waqar et al. 2024).

Waqar et al. 2024 is highlighting importance of collective, multi stakeholder projects for crop genetic diversity.
This could include:

- ongoing collective action towards suitable accessible genetic resources for climate resilient vigorous rootstocks. Additionally to trait-oriented collection of veteran apple trees that was conducted in the present project, habitat based collections as suggested by Cortes to not only target spatial gaps but prioritize regions that could have promoted favourable selection of apple trees and rootstocks towards climate resilience related traits – in Germany and beyond.
- open data accessibility for projects that are pursuing climate resilience in development and breeding of vigorous rootstocks.
- Participative projects of selecting, evaluating and probably breeding of climate resilient vigorous rootstocks, that could be operationalized with the tricot approach an “agile framework for decentralized on-farm testing supported by citizen science” to breed “demand driven” (Voss et al. 2025; Sousa et al. 2024)
- Ongoing collective action could be incorporating a continuation of veteran tree assessments, assessments of other genetic resources, international corporations for example.

The data of the present project is aimed to be made accessible via an open platform hosted by the German Association on pomologists. The data will be displayed as an extra layer of a map tool, that is normally used to document *Streuobst* meadows and their maintenance status. Additionally, it could allow ongoing assessment of veteran apple trees. To assure private data security and data sovereignty, coordinates could be shortened and contact details of the tree’s owners could be used obscured to allow the latter to contact interested researchers or practitioners deliberately (Meinolf Asshoff, German Association on Pomology, personal communication, 2025).

The input data could be augmented with relevant grid data as discussed earlier, to enhance it's informative value. A download option of the complete dataset alongside with the description of the data origin could be made accessible in a simple **table** format with filter functions. The data or a future dataset with more veteran trees could also be considered predestined for a multivariate analysis of variance (Kruppa-Scheetz 2025) to identify candidates that are showing a strong vitality exceeding the expectations that can be explained by the included factors.

Candidates of interest should be tested regarding their genetic identity to verify if rootstock and scion are distinct and choose means of propagation accordingly. For utilization in breeding programs, establishment in vitro to eliminate diseases and marker assisted parent selection should be utilized (Hanke; Flachowsky 2017; Marini 2024). A screening for heat tolerance as suggested by Park et al. 2024could be used as a selection factor, as heat is a factor homogenously increasing all over the world with less regional exceptions than other results of climate change.

In accordance to many participants requests throughout the present project, asking whether veteran pear or cherry trees could be submitted as well, similar projects to assess the diversity of veteran pear and other fruit trees should be aimed for. Due to its high popularity, apples are concerned by maintenance of landraces more often (Calvet-Mir et al. 2025; Raggi et al. 2022). Apple trees were chosen for the present, initial attempt of citizen science based veteran rootstocks assessments, but other fruit crops should follow, as they are just as important in terms of agrobiodiversity and cultural significance.

5. Conclusion

Vigorous rootstocks that are capable supporting standard apple trees in a climate change future are exposed to multiple and partly antithetic requirements, concerning their physiology, adaption to abiotic and downstream biotic stressors as well as vigour, architecture, propagation propensity, and scion compatibility. Requirements imposed by potential innovative growing systems were not considered in this thesis. Veteran apple trees planted in the 1930s or earlier that are selected trait specific and with emphasis on their current and historical growing conditions are very likely to embody unknown and worthy genetic resources, that have been preselected by domestication and the circumstances they were witnessing during their lifespan. In the present project, georeferencing and description of veteran apple trees and their growing sides was realized in a digital assessment protocol in the *jotform* online tool. The protocol was adapted to advanced participants and embedded in an introducing and concluding online meeting for community building, networking, and knowledge exchange. 154 trees collected in this project, though being clustered in few regions of Germany, Switzerland, Austria, and Slovakia, showed a wide variety of age, vigour, vitality, proportions, leaf characteristics, phenology in relation to various environmental factors. Annual rainfall, altitude, and soil water retention index were added with grid data. Difficult perceptibility of old grafting marks, interactions between rootstock, scion and environment are additionally complicating the interpretation of the collected data. Specific potentials can only be the outcome of more in-depth surveying conducted with selected candidates. Citizen science is offering a wide range of different tools and agile frameworks that are assuring quality and usability of the data, that can be collected with thoughtfully recruited participants. The exemplary assessment project belonging to this thesis was attracting a wider spectrum of interested persons than valuable, contributing roles had been defined for. It is concluded, that mass approaches should be utilized alongside with specialized assessments with advanced participants. Also, a longer timespan or continuous collection should be aimed for, to effectively search out promising trees and describe their most relevant characteristics to promote physical collection, preservation and potentially usage. Trainings for participants with long term commitment, a condensed assessment protocol and augmentation with additional grid data describing air temperature, heat events, humidity, and soil moisture could greatly improve the data output quality. Envisioning the future path from collection of genetic resources to the admired rootstocks for climate resilient vigorous apple trees: participatory and regional approaches of selection, breeding and evaluation of rootstocks could have the potential to meet the requirements imposed by highly insecure and inhomogeneous future climate conditions and use cases of standard apple tree

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7. Appendix

The **appendix** is created digitally only according to supervisor's recommendation

Nr.	Data description
1	Search strings for literature research
2	Databases overview
3	Protocol literature research
4	Data security and insurance statement
5	Criteria and selection of veteran apple trees
6	Aerial views
7	Assessment protocol
8	List of multipliers
9	Advertisement material
10	Registration form
11	Introduction online workshop slides
12	Record of introduction online workshop
13	Data and R scripts
14	Feedback form
15	Feedback responses