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Research report

Increasing climate change resilience through sustainable agricultural practices

Evidence for wheat, potatoes, and olives

Institute for European Environmental Policy

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ABBREVIATIONS

CAP	Common Agricultural Policy
cm	Centimeter(s)
CO_2	Carbon dioxide
CPB	Colorado potato beetle
CT	Conventional tillage
dt/ha	Deciton per hectare
EAFRD	European Agricultural Fund for Rural Development
EASAC	European Academies Science Advisory Council
EC	European Commission
EEA	European Environment Agency
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GAEC	Good Agricultural and Environmental Conditions
GHG	Greenhouse gas
ha	Hectare(s)
INRA	Institut National de la Recherche Agronomique
IOC	International Olive Council
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogramme(s)
MedEC	Mediterranean Experts on Climate and Environmental Change
Mha	Million hectares
MLUK	Ministerium für Umwelt, Naturschutz und Klimaschutz Brandenburg

mm	Millimeter(s)
µmol mol	Micromole
Mt	Megatonne(s)
MT	Minimal tillage
NT	No-tillage
RCP	Representative Concentration Pathway
SOC	Soil Organic Content
SOM	Soil Organic Matter
t/ha	Tonnes per hectare
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change

EXECUTIVE SUMMARY

Climate change is happening. The year 2023 was characterised by contrasting extremes which demonstrate this: heavy rains in springtime caused flash floods in many European regions, the Mediterranean suffered under extreme heat and wildfires during the summer, and in September torrential rain and floods devastated Greece, Bulgaria, and Turkey, while much of Northern Europe saw heavy winds and flooding in October.

Whilst all economic sectors will be, and already are, impacted by climate change, agriculture is considered particularly vulnerable. The **European Union (EU) is one of the world's largest producers and exporters of agricultural products (EEA, 2019) with a large share of the food produced prepared and eaten in kitchens around Europe.**

Wheat, potato, and olives – central to European farms and kitchens

Wheat (flour) is used to prepare many **key 'ingredients' of many European cuisines such as baguette in France or pasta in Italy**. In 2022, the European Union (EU) produced approximately 133,8 Mt of wheat, representing 16,7% of global wheat yields (Agreste, 2024).

Europeans top the table of potato consumers worldwide, with each European eating **90kg per year on average**. As a low-fat food, rich in protein, starch, minerals, and vitamins and with a caloric density higher than any other commercial crop, it plays a key role in global food security. The **EU is the second largest producer globally** (37% of total production) (Eurostat, 2021).

95% of all olive trees in the world are cultivated in the Mediterranean region. Of the a**pproximately 3 million tonnes of olive oil produced every year worldwide, the EU supplies around 68%;** in addition, the bloc produces 866 thousand tonnes of table olives per year. **Around 50% of the world's production of olive oil is consumed in the EU** (Eurostat 2023). Although it is recognised that the Mediterranean Basin encompasses many different cultures and regional cuisines, **olive oil is at the core of the Mediterranean Diet.**

In recent years, the EU output of many key agricultural commodities fell sharply due to widespread droughts and other adverse weather conditions. Without measures to mitigate and adapt to climate impacts, farmers might be forced to switch to alternative crops. In the long run, this could not only change what and how we farm in some regions in Europe but also reshape our national cuisines.

Impacts of climate change on wheat, potato, and olive production in Europe

CO_2 fertilisation is thought to positively influence wheat, potato and olive growth and yields by minimising water loss through transpiration. However, it is **uncertain if and to what extent the impacts of heat, drought and heavy rain might offset these positive effects**.

An assessment of historic data by Helman and Bonfil (2022) shows that CO_2 increases from 1961-2019 increased yields by 7% in the top-twelve wheat growing countries but **warming of 1.2°C combined with water depletion lowered yields by 3%**.

Potatoes are **extremely drought and heat-sensitive**: temperatures above 30°C during the growing season can significantly **decimate the number and size of potatoes** and cause **physical defects** such as hollow heart, tuber cracking, and skin russeting. **Germany is the top producer of potatoes in the EU,** producing a total of 10.3 million tons of potatoes in 2022 (Eurostat, 2021). However, **due to the extremely dry weather** throughout the entire growing season, **yields per hectare reached a historical low in 2018** at 353.8 decitons per hectare (dt/ha) and **were only slightly higher in 2019** at 390 dt/ha (Nimmrichter, 2021).

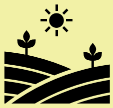
Higher temperatures, especially during winter, and lower precipitation are **thought to affect olive flowering**. With increasing temperatures and shifting seasons, flowering is likely to advance and could potentially become out of sync with the life cycle of pollinators. In **2022**, the total harvested production of olives (for olive oil) in the EU was 7.6 million tonnes, 4.6 million tonnes less than the previous year’s production level and the **lowest harvest since 2000** (Eurostat 2023).

Food is more than nourishment: it is central to European national identities, with culinary diversity often seen as one of the continent's most appealing characteristics (Anderson et al, 2016). By **making agricultural production in Europe more resilient to climate change**, we will therefore not only ensure that farming in Europe continues, but we **will also contribute to preserving Europe's diverse regional cuisines.**

Whilst agriculture is particularly vulnerable to climate change, it also has a particularly strong adaptation potential (EEA 2024). For instance, projections of climate change on potato yields vary, ranging from global yield declines of 2% to 6% by 2055 (without adaptation) and increases of 9% to 20% globally (with adaptation) by 2050. Building up the resilience of farming systems requires that short and long-term climate adaptation strategies are implemented at different scales, and drawing on a full range of knowledge, financial, technical, and cropping actions, and practices (Alvar-Beltran et al, 2021; Devot et al, 2023). Our review of the evidence for wheat, potatoes and olives found that **sustainable cropping practices have the potential to maintain and improve soil and water parameters that can buffer farming systems against current climate risks and adapt to future climatic conditions**.

More importantly, the **evidence suggests no significant negative impacts on crop outputs when compared to conventional farming methods**. The scientific literature shows that the reviewed practices hold significant potential for maintaining, or in some cases, even improving wheat yields, as compared to conventional monocropping. Wheat crops are better able to withstand the negative impacts of hazards, such as heat stress, drought, or pests. For potatoes, field trials with mulching generated increased or at least equal output levels when compared to non-mulched plots, also under hot water scarce conditions. Higher yields of up to 30-40% were reported (Adamchuk et al, 2016). Mixed/intercropping studies find no negative effects on either the saleable yield or the quality of the potatoes. Field experiments in olive plantations indicate that cover crops, especially when combined with mulching no-tillage, and sustainable pruning, may maintain and even improve olive yields

How sustainable cropping practices impact ecosystem functions that increase resilience of wheat, potato, and olive cultivation



Crop rotations can positively impact soil organic carbon and nutrient cycling and prove particularly beneficial for reducing the prevalence of weeds, pests and diseases in wheat and potatoes. **Intercropping** can help to improve water use efficiency, control soil erosion, and enhance the suppression of weeds, pests and diseases in wheat and potatoes. **Agroforestry** provides shelter to wheat from extreme heat, can improve soil water distribution and reduces the negative impacts from floods. **No-tillage** has been associated with greater soil water retention and soil organic matter, as well as nutrient conservation and lower soil erosion in wheat cultivation **Mulching** may lower soil temperatures and help maintain soil water moisture in hot and dry conditions, as well as increase the resilience of potato and olive cultivations to heat and drought. **Cover crops**, combined with other sustainable practices, might decrease soil losses, thus increasing water and nutrient retention capacities, improving resilience of olive cultivation to water scarcity. The physical barrier created by cover crops can further reduce soil losses from surface run-off and help lower soil temperatures.

The **Common Agricultural Policy (CAP) requires (and compensates) for the uptake of many of these practices** through minimum standards, the Good Agricultural and Environmental Conditions (GAECs (e.g., GAEC7 on crop rotation). In addition, it incentivises their uptake through e.g., eco-schemes. **However, in light of the Ukraine war, Member States were allowed to deviate from mandatory requirements in the name of food security**. Since the start of 2023, a major wave of **protests by farming organisations** in many Member States and Brussels has prompted the European Commission to seek the **weakening of mandatory standards on habitat for nature and crop rotation** from the current CAP and introducing **significant flexibilities to others relating to soil management**.

At the same time, the **Commission has, from the 1st of January 2014 to the end of 2023, channelled more than €2.5 billion of EU funds to the EU agricultural sector to support farmers** impacted by effects from COVID-19, the Ukraine war and extreme weather occurrences, events, which they describe as multidimensional and unpredictable (European Commission, 2024). However, **distributing (more) money to farmers while advocating for lower environmental standards suggests that we are dealing with extraordinary circumstances** where a choice needs to be made between protecting biodiversity and ecosystem functions and food security (Willard, 2023). Yet, the evidence and the experience of recent years show that **climate change is here to stay, and urgent action is needed to facilitate a transition towards a more resilient European farming** sector that has the capacity to operate under and adapt to future climatic conditions.

Our review of the evidence shows that, at least for the studied cropping practices and crops, that **sustainable practices have the potential to contribute to the two important societal objectives of maintaining current levels of food production and conserving and improving ecosystem functions and features, which is considered key to farm system resilience**.

It is essential that steps be taken to support farmers and households engaged in agriculture to cope with both the threat of climate variability as well as the challenges that climate change will pose on future livelihood opportunities. Climate change is not a singular event. **Policy instruments should focus on facilitating a wider uptake of practices that improve those soil quality, water conservation as well as landscape and biodiversity parameters that will potentially enhance the climate change resilience of farming systems**. Member States are required to dedicate 25% of CAP direct payments to eco-schemes, and a minimum of 35% of European Agricultural Fund for Rural Development (EAFRD) funding is ring-fenced for environmental, climate and animal welfare objectives. Countries should use the flexibilities provided under the current CAP to **design interventions that incentivise farmers to take up those practices that have proven to increase resilience to the specific climate risks projected to affect their region**. This type of targeted support is especially needed to help farmers with up-front investment needs to transition to new agricultural methods.

Identifying the most appropriate practices for different environmental and (current and future) climatic conditions warrants further research. A more comprehensive review covering different types of crops and practices, ideally drawing from national research efforts, could provide valuable insights into the benefits of different practices under different regional conditions. Such a review should also cover the economic implications of adopting sustainable practices, as the literature on the costs of transitioning to and applying new practices is still limited.

The evidence demonstrates that the **positive effect of practices on parameters which enhance resilience and yields depends on a wide variety of factors and is context-specific.** Such factors include environmental conditions, soil types, crop and tree species, the time of planting crops, as well as plant density, among others. Inappropriate agronomic management choices can be detrimental to crop yields or result in a failure to deliver environmental benefits. **Farmers may lack knowledge** regarding the suitability of crop combinations (in intercropping), crop-tree combinations (in agroforestry), density of crops and trees, the selection of practices under specific pedoclimatic conditions, the best time of the year to sow or harvest crops, etc. Hence, **Member States need to support farmers to develop tailored plans for improving sustainability and resilience and invest in increasing their advisory capacity.** Knowledge-sharing platforms and workshops may help to facilitate farmer-to-farmer dissemination of know-how on sustainable practices that is relevant to their circumstances.

1. INTRODUCTION

Climate change is happening. The year 2023 was characterised by contrasting extremes which demonstrate this: heavy rains in springtime caused flash floods in many European regions, the Mediterranean suffered under extreme heat and wildfires during the summer, and in September torrential rain and floods devastated Greece, Bulgaria, and Turkey, while much of Northern Europe saw heavy winds and flooding in October.

The increasing frequency and intensity of these events is mainly driven by human activity. Assessments show that climate change played a role in 93% of all heatwave events that have been recorded in Europe since 2000 (Carbon brief 2022). Long-term observations confirm the continuing warming trends for both annual and seasonal averages for the whole of Europe. Between 2013 and 2022, European land temperatures have increased by 2.04 to 2.10°C, compared to the pre-industrial level. **The ten warmest years on record for Europe have all occurred since 2000, and the five warmest years have all occurred since 2014** (EEA, 2021, The Copernicus Programme, 2023a).

In Europe, **agricultural production has been identified as the economic sector most sensitive to climate change risks** (Giannakopoulos et al, 2009; Karamanos et al, 2011). Higher atmospheric CO_2 concentrations, increased temperatures, altered precipitation and transpiration regimes, and more frequent and severe extreme events, together with increased weed, pest, and pathogen pressures, are expected to affect crops, although the extent of these reductions will differ between regions and crops[1] (EEA 2019). While impacts on agricultural outputs might be relatively small at the European scale (at least for the first half of this century), regional differences might lead to a decline in the production level of crops or crop varieties specific to some areas and significant price increases.

The European Union (EU) is one of the world's largest producers and exporters of agricultural products. The block typically supplies one-eighth of the global cereals output, two-thirds of the global wine, and three-quarters of the world's olive oil production (EEA, 2019, Eurostat, 2023). **In 2022, however, the EU output of many key agricultural commodities fell sharply due to widespread droughts**: cereal outputs were down by 9% and olives for oil by 38% (Eurostat, 2023).

[1] Climate impact assessments for Europe identify, for example, grain maize as one of the most strongly impacted crops, with the highest reductions forecast for southern Europe. On the other hand, wheat yields are projected to increase by 5–16% in central and northern Europe and decrease by 10–25% in southern Europe (EASAC, 2022).

Without measures to mitigate and adapt to climate impacts, farmers might be forced to switch to alternative crops, requiring them to make significant capital investments in new production systems. **In the long run, this could not only change what and how we farm in some regions in Europe, but also reshape our national cuisines** (see Box 1).

Box 1. No more risotto? How climate change threatens an iconic Italian dish

Italy produces about 50% of the rice grown in the EU, most of it in the Po valley in the north of the country. In 2022, rice production fell by more than 30% as the fields where traditional risotto rice varieties, such as carnaroli and arborio, are grown turned brown. The region went through the worst drought in 200 years. The production of carnaroli, a refined rice variety which is extremely vulnerable to changes in climatic conditions, fell by 50%. Carnaroli and other varieties are the crucial ingredient in traditional Italian risotto as they have a unique ability to absorb seasoning and aroma. However, in light of the changing climate - 2023 was yet another year of climate extremes where drought was followed by torrential rain and flooding - farmers have started to turn to other crops such as maize to maintain an income[2]. In 2023, around 211,000 hectares were sown with rice, the smallest area for 23 years. Comprehensive mitigating and adaptation strategies will need to be implemented if rice cultivation is to continue in Italy. Rise is a water-intensive crop requiring between 3,000 and 10,000 litres of water per kilogram of output. Increasing the collection of rainwater and the use of alternative water sources is one potential strategy to ensure that Italy can continue to grow its unique risotto rice varieties[3].

[2] Risotto crisis: the fight to save Italy's beloved dish from extinction, The Guardian, 29.02.2024, https://www.theguardian.com/environment/2024/feb/29/risotto-crisis-the-fight-to-save-italys-beloved-dish-from-extinction-aoe#:~:text=That%20year%2C%20Italy%20lost%2026%2C000,of%20rice%20fields%20was%20lost., accessed 01.03.2024.

[3] Italy to cut rice output as drought looms for second year, WHTC, 24.03.2023. https://whtc.com/2023/03/24/italy-to-cut-rice-output-as-drought-looms-for-second-year/, accessed 02.04.2024.

Of course, national cuisines evolve over time, and as consumers are becoming increasingly aware of the environmental footprint of their diets, an interest in plant-based eating and novel foods is emerging. However, as many commentators note, **food is more than nourishment** and central to our national identities and "*culinary diversity may be one of the most appealing aspects of European culture*" (Anderson et al, 2016, p.15). By making agricultural production in Europe more resilient to climate change, we will therefore not only ensure that farming in Europe continues, but we will also contribute to preserving Europe's diverse regional cuisines.

Scope and objectives of the report

At farm-level, there are several **sustainable cropping practices that can ensure that arable crop production is robust enough to buffer against current climate risks and to adapt to future climatic conditions**. These practices have the potential of maintaining and improving the state and function of natural resources that farming relies on and which are systematically being degraded by the continued use of conventional methods, such as intensive tilling, leaving soils bare, or high chemical inputs.

The Common Agricultural Policy (CAP) requires (and compensates) for the uptake of many of these practices through minimum standards, the Good Agricultural and Environmental Conditions (GAECs (e.g., GAEC7 on crop rotation). In addition, it incentivises their uptake through e.g., eco-schemes. However, in light of the Ukraine war, Member States have been allowed to deviate from mandatory requirements in the name of food security. Derogations which were adopted for 2023 are set to continue for the year 2024. **At the same time, the Commission has, from the 1st of January 2014 to the end of 2023, channelled more than €2.5 billion of EU funds to the EU agricultural sector to support farmers impacted by effects from COVID-19, the Ukraine war and extreme weather** occurrences, events, which they describe as multidimensional and unpredictable (European Commission, 2024). Since the start of 2023, a major **wave of protests by farming organisations** in many Member States and Brussels has **prompted the European Commission to seek the weakening of mandatory standards** on habitat for nature and crop rotation from the current CAP and **introducing significant flexibilities to others relating to soil management.** However, distributing (more) money to farmers while advocating for lower environmental restrictions suggests that we are dealing with extraordinary measures for extraordinary circumstances. Yet, the evidence and the experience of recent years show that climate change is here to stay. Crisis payments do not offer the long-term solutions that are needed to increase the resilience of the agricultural sector. Whilst it is generally assumed that sustainable farming systems are lower yielding and more labour intense, sustainable practices do offer the potential to increase climate resilience in the long run, thus reducing the need for ad-hoc financial measures.

Against this background, this report aims to compile and disseminate results from scientific studies that document the effectiveness of sustainable practices to enhance the resilience of selected arable crops and showcase how these practices are successfully used by farmers.

Section 2 describes **how climate change is expected to impact farming in Europe** in the decades to come and provides an overview of strategies and actions which could **enhance the resilience of farming systems**, with a focus on **sustainable cropping practices**, i.e. crop sequencing, and arrangement and management techniques that are thought to increase resilience to climate change risks through positive effects on diversity, soil quality and water parameters (see Box 2 for definitions of the key concepts used throughout the report).

As explained above, the way in which **climate change will** affect agricultural production and outputs **will differ between crops and region**. By the same token, if and how sustainable practices will increase the resilience of farming, depends on the specific cropping system and agro-environmental conditions (European Joint Programme SOIL, 2022). **Section 3** examines the impacts of different climate risks on three major agricultural crops which are staples of different European cuisines: **wheat, potatoes, and olives.** Drawing from a range of sources, including the scientific literature, outputs of research projects, reports from the European Commission and its agencies, as well as the wider media, we present evidence of the extent to which sustainable practices affect key soil, water and diversity parameters which are thought to enhance resilience and yields. In terms of geographic scope, the review favoured evidence obtained in Europe. Where information was scarce, we consulted studies from other regions of the world to compare findings.

Section 4 presents **conclusions** on whether the investigated practices can increase climate change resilience of wheat, potato, and olive cultivation in the EU and formulates **recommendations** for future research, policy, and practitioners.

Readers should interpret our findings with care. First, we only reviewed small portion of a substantial body of research on sustainable copping practices, and their effects on different environmental parameters and yields. The focus was on practices that have been tested for wheat, potatoes, and olives in European climatic and soil conditions. Findings reported from other parts of the world might therefore contrast with the conclusions presented here. Second, given the language capacities within the research team, there is a bias towards certain languages and EU countries in the studies we consulted.

Finally, it should be emphasised that this report focuses on **cropping practices** that may increase resilience of farming systems. These practices are one set of actions which **should be used combination, with other approaches for an optimal outcome**. In addition, **actions are needed at regional/national scale**. Moreover, for production is only **one link on the agrifood value chain**. The extent to which farming operations can develop the different capacities to be truly resilient to climate change depends on and is shaped by the actions taken by other actors on the chain.

2. THE NEED FOR CLIMATE CHANGE RESILIENT AGRICULTURE IN EUROPE

The relationship between agriculture and climate change is sometimes described as a two-way relationship (e.g. Yohannes, 2016; Pal et al, 2019). Agricultural activities depend on favourable climatic conditions; any change in conditions will thus affect production. At the same time, greenhouse gas (GHG) emissions from farming contributes to climate change. Tillage practices, fertilisers, livestock manure, and fossil fuels for running machinery and energy emit carbon dioxide, methane, and nitrous oxide (Yohannes, 2016). However, the relationship between agriculture and climate change is more complex, and multidimensional. Rockström et al (2020) effectively argue that while **agriculture is currently the largest single source of environmental degradation and biodiversity loss [globally], it is also likely to be the biggest victim of this degradation**. The loss of natural ecosystems due to their conversion to cropland and pasture, coupled with the impacts of agricultural pollution, severely threatens those ecosystem services that are the foundation of agriculture itself. **And by degrading ecosystem functions, agricultural systems become less resilient, meaning that their "ability […] to anticipate and prepare for, as well as adapt to, absorb and recover from the impacts of changes in climate and extreme weather" is decreased** (Alvar-Beltran et al, 2021, p.1). By the same token, agriculture has the potential to increase significantly Europe's resilience through the adoption of mitigation and adaptation actions (Yohannes, 2016; EEA 2024).

Changing climate conditions and extreme events are affecting agriculture

Farmers are already experiencing climate change: warmer average temperatures are extending growing seasons and frost-free periods; plants start to flower earlier in the year, potentially becoming exposed to late frost; heavy rain and flooding delay or prevent harvesting leading to crops rotting in the fields (Zhao et al, 2022). The consequences are tangible; between 1976 and 2005, changes in temperature and radiation caused a significant decline of potato, wheat, maize and barley in Italy and southern-central Europe (Supit et al, 2010), and grape yields in the north-east of Spain have been decreasing since the 1960s due to increasing water scarcity (Camps and Ramos, 2012). **The severe droughts experienced in the EU in August 2022 led to large losses in agricultural production, averaging 5-10% declines for crops like grain maize, sunflower and soybeans** (Baruth et al, 2022).

Losses are not only occurring in southern Europe. Heavy rainfall in July of 2021 in Belgium and Germany led to severe floods, with the costs to private households, infrastructure, forestry, and agriculture, as well as viticulture enterprises estimated at 33 billion euros (Fekete and Sandholz, 2021). The total amount of damages to winegrowers and agriculture alone is thought to amount to 200 million euros[4]. Damages resulting from extreme weather events on the whole EU economy since 1980 are estimated to be around 487 billion of euros, with agriculture being the most affected sector (EEA 2022).

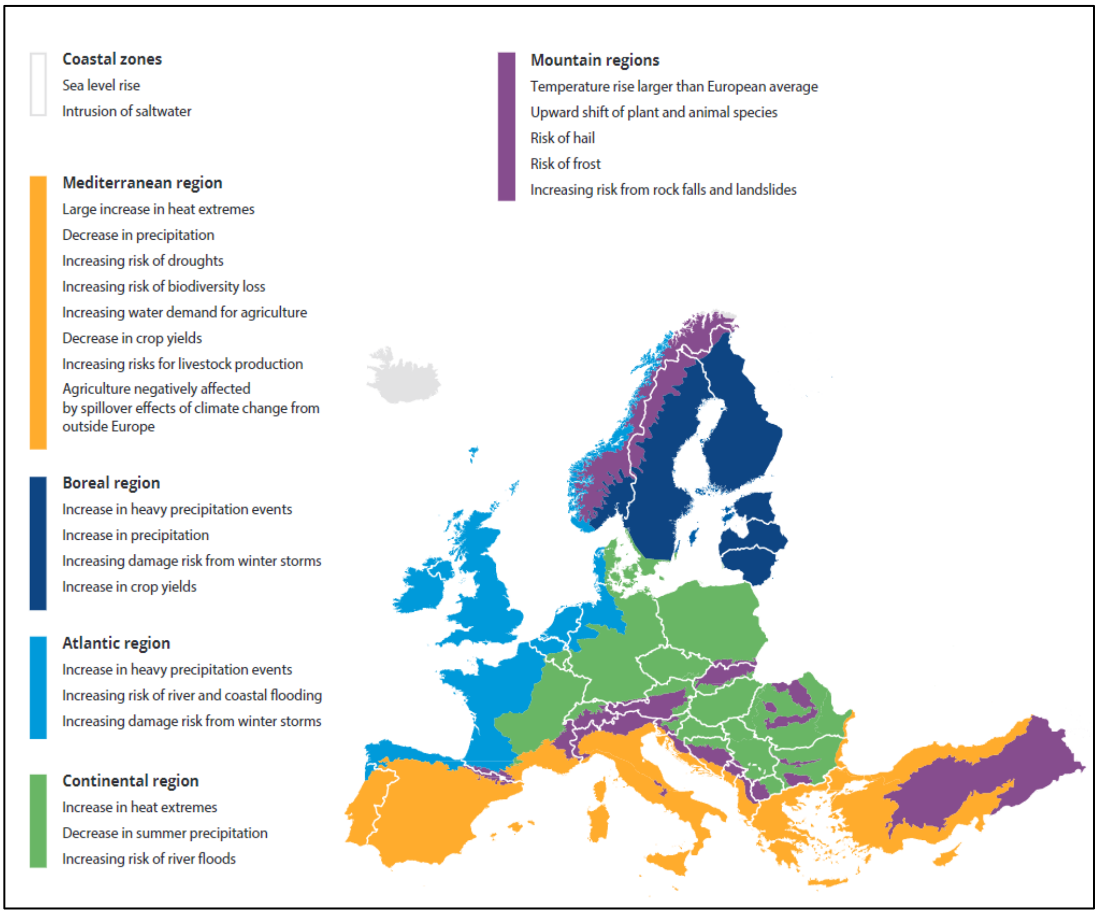
Looking at these statistics, the evidence is clear: the climate is changing, and extreme weather events are neither new nor singular events. **In the decades to come, the warming trend in Europe means that farmers will operate under climatic conditions that are fundamentally different from those of today and will pose significant challenges to crop management** (Ceglar et al, 2018; Trnka et al, 2011). The impact of climate change on agriculture will vary across Europe with the Mediterranean region likely to be most severely affected by temperature increases, a decline in precipitation, extreme heat, droughts, and biodiversity losses (see Figure 1).

For instance, the number of heatwave days "could increase thirtyfold in the future compared to the 1971 – 2000 reference period" (Devot et al 2023). In contrast, while northern Europe is expected to experience some negative effects such as more frequent heavy rainfall and flooding, an overall increase of yields due to higher temperatures and longer growing seasons is projected (Midler, E. 2022). These effects could lead to an agriculture intensification in Northern and Western Europe, especially regarding crops, as well as land extensification and abandonment in Southern Europe because of the reduction of agriculture profitability. Moreover, the simultaneous occurrence of these events will reduce

[4] Nach der Flut im Ahrtal. Winzer und Landwirte beklagen 200 Millionen Euro Schaden, https://ga.de/region/ahr-und-rhein/mehr-von-ahr-und-rhein/ahrtal-flut-winzer-und-landwirte-beklagen-200-millionen-euro-schaden_aid-72493699, accessed 24.01.2024.

the capacity of agricultural systems to buffer other extreme weather events, a phenomenon referred to as a “cascading system”. For instance, if a region suffers from drought and heatwaves, the capacity of the soil in this region to absorb water will be reduced and thus worsening the impacts of heavy rains and floods (EEA, 2019).

Figure 1. Main climate impacts on the agriculture sector for the main biogeographical regions in Europe



(Source: EEA, 2019)

As a result, **economic losses from heatwaves are likely to increase fivefold by 2060** (García-León et al. 2021) and could reach 28.6 billion euros per year by 2100 under pessimistic scenarios (Naumann et al. 2021). Increasing drought and heatwaves will reduce the yield of warm-season vegetable and tree crops with high water requirements (EASAC 2022), with rainfed agriculture likely to face more climate-related risks than irrigated crops (Toreti et al, 2019: Trnka et al., 2011).

Against this backdrop, making the agriculture sector more climate change resilient becomes imperative.

How can agricultural systems become more resilient to climate change?

In the context of this study, we define resilience as “the ability of an agricultural system to anticipate and prepare for, as well as adapt to, absorb and recover from the impacts of changes in climate and extreme weather” (Alvar-Beltran et al, 2021, p.1). Resilience is thought to encompass three types of capacities (robustness, adaptability, and transformability) (Zurek et al, 2022; Meuwissen et al, 2019) (see Box 2).

Box 2. Three different resilience capacities -Robustness, adaptability, and transformability,

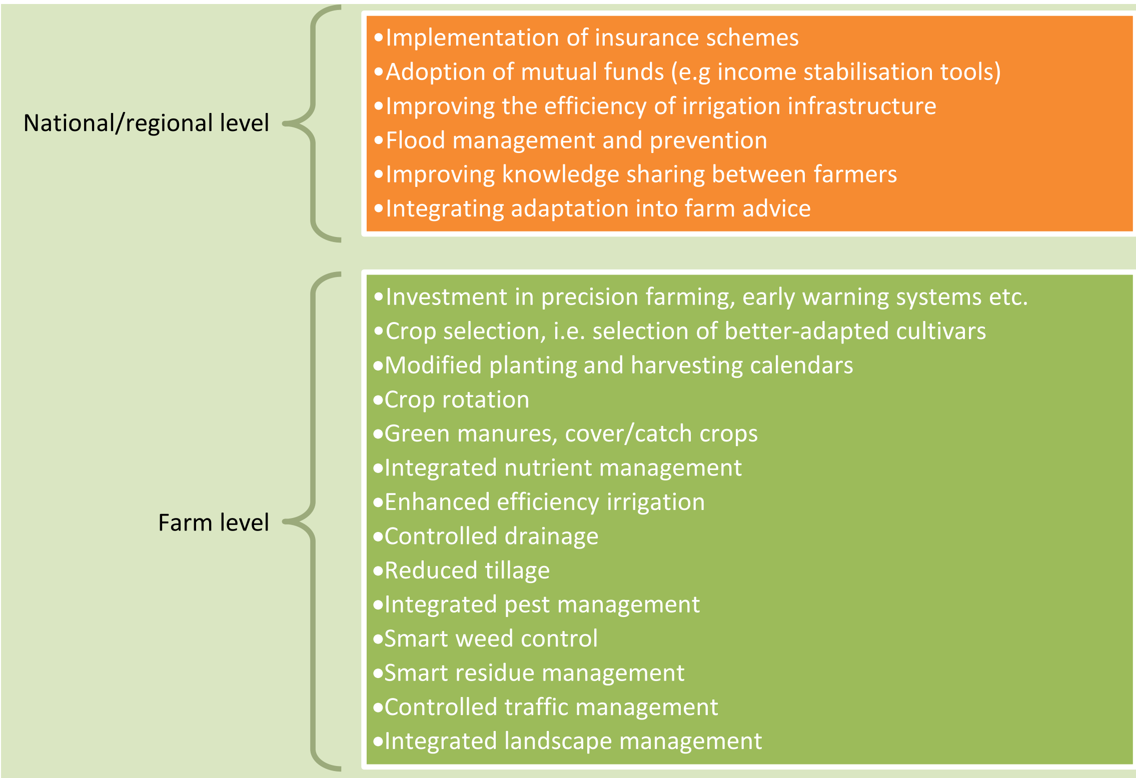
Robustness refers to a farming system’s ability (i.e. social, economic, and biophysical) to maintain the expected outputs (i.e. consistency) regardless of the impact of perturbations. It can be broken down into three elements: avoiding exposure, withstanding exposure, and recovering from exposure.

Adaptability describes a farming system’s capacity to adjust its response when faced with disruption while maintaining key system functionalities. Strategies to increase adaptability are learning and experimenting, flexibility in the farm (business) organisation, and diversification to spread risks and create buffers on the farm (including income diversification).

Transformability is understood as the capacity to create a new system when ecological, economic, or the social structures make the existing system untenable. The biophysical environment in which farming takes place is a key determinant of transformability, for instance, practices that impede the ability to reverse land use changes (e.g. soil sealing) or contaminate soil need to be avoided.

Building up the resilience of farming systems requires that short and long-term climate adaptation strategies are implemented at different scales, and drawing on a full range of knowledge, financial, technical, and cropping actions, and practices (Alvar-Beltran et al, 2021; Devot et al, 2023). Figure 2 presents a selection of broad categories of adaptation measures which can be taken up at national, regional, and farm level.

Figure 2. Overview of different types of adaptation measures with the potential of increasing resilience of the agriculture sector



(Source: compiled from EEA 2019, Devot et al, 2023, Oenema et al, 2017)

Sgarbi and Nadeu (2023), highlight **the importance of selecting actions and practices that increase general rather than specific resilience**. Stresses and shocks can evolve over time, making specified resilience obsolete if no longer adapted to unforeseen and unpredictable perturbations. For example, technological solutions targeting specific stresses require several years to develop and may be outdated by the time they reach the market. The authors stress the crucial role cropping practices play in maintaining and improving the state of the natural resources as a key determinant of general resilience at farm level:

1. A farming system's **robustness** to stresses and shocks can be increased though practices which reduce for instance the exposure of soils to heavy rainfall, such as cover crops and mulching.

2. Practices that contribute to soil health and the building up of organic matter can increase the **adaptive capacity** of farming systems. Using cover crops and green manure, for example, can increase the soil's buffering capacity and ability to sustain a diversity of crops under changing environmental conditions.
3. The state of a farming system's natural resources determines the extent to which it can be transformed. The more a farming system is degraded, the lower its capacity to transform. Cropping practices that maintain crucial ecosystem functions are a key determinant of a farming system's level of **transformability.**

As it stands, conventional arable farming – which we acknowledge includes many different configurations - typically uses practices that contribute to the degradation of ecosystems and their functions, thus limiting their climate change resilience (see Box 3).

Box 3. Conventional farming is not resilient to climate change hazards

- In 2016, 5.9% of the EU's agricultural land - and up to 30% of the UAA in southern European countries – was irrigated. While the agricultural land equipped with the necessary infrastructure is larger in most regions (and could be expanded), evidence shows that increasing **irrigation** cannot compensate for losses caused by anticipated water scarcity (e.g. Bednar-Friedl et al., 2022; Egerer et al, 2023).
- **Crop specialisation and simplified arable rotations** reduce structural and ecological heterogeneity in the landscape, and thus the abundance and diversity of natural enemies to pests (Altieri et al, 2015).
- Two-thirds of the EU's arable land is tilled with **conventional tillage** practices (2016 data) (Eurostat, 2020a) which disturbs the soil structure and subsequently its water retentiona and filtering capacity.
- About 23% of arable land was left without **soil cover** during winter, increasing the risk of soil erosion, nutrient, and pesticide run-off (Eurostat 2020b).
- **Pesticides** may increase pest outbreaks by negatively affecting natural enemy communities and driving pesticide resistance. **Herbicide** use generally reduces weed abundance and species richness.
- **Natural or semi-natural landscape features** provide important biodiversity and ecosystem services, e.g. pollination, soil erosion control and water flow regulation. Only 5.6% of agricultural land in the EU is currently covered by landscape features (2022 data) (D`andrimont et al, 2023).

What role can sustainable farm-level cropping practices play?

Several **farm-level cropping practices** with the potential of enhancing resilience to climate change risks can be identified from the literature. Table 2 lists those that are most frequently mentioned in existing studies and reviews as having the potential of increasing climate change resilience of farming. When talking about resilience of farming, strategies like expanding irrigation, breeding new cultivars or transitioning to different crops take a prominent place in the literature. While these might form part of a comprehensive strategy to increase resilience, they are long-term activities, e.g. the development of new varieties usually takes around 10 years. In contrast, the practices below offer short-and medium-term solutions to enhancing farm-level resilience. Different authors refer to these or some of these practices under the umbrella of broader concepts such as agroecology (Altieri et al, 2015), climate-smart agriculture (Alvar-Beltran et al, 2021), conservation farming, and more recently, 'regenerative farming' (Kurth et al, 2023). One common aspect of these practices is that they give priority to long term objectives (e.g. soil quality and biodiversity) over short-term ones, such as immediate yield (EASAC 2022).

Table 1. Selected practices thought to increase climate change resilience at farm level

Sustainable practices	Description
Mixed/ Intercropping	Cultivating two or more crop species (i.e., crop mixture cropping) or genotypes (i.e., cultivar mixture cropping) in the same area and coexisting for a time so that they interact agronomically.
Agroforestry	Agroforestry is a particular type of land-use system and technology where woody perennials (trees, shrubs, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals.
Crop rotation	The practice of alternating crops grown on a specific field in a planned pattern or sequence in successive crop years, so that crops of the same species are not grown without interruption on the same field.
Landscape features	Landscape features are small fragments of natural or semi-natural vegetation in agricultural landscapes, providing ecosystem services and biodiversity support.
Cover/ catch crops	(Nitrogen-fixing) crops grown over winter or other periods when the land would otherwise be bare and susceptible to soil losses.
Reduced/ no-tillage	Reduced tillage refers to methods involving low degrees of soil disturbance (e.g., minimum tillage, subsoil tillage, non-inversion, or shallow inversion). No-tillage (or zero tillage) is a minimum tillage practice in which the crop is sown directly into soil not tilled since the harvest of the previous crop.
Crop residue management	Crop residue management is the handling of stems, leaves, chaff, and husks that remain in the fields after crops are harvested for grain, seed, or fibre. Residues can be retained at the soil surface or incorporated into the soil.
Mulching	Covering the topsoil with material such as leaves, grass, twigs, crop residues, or straw. Plastic film is also commonly used for mulching in agricultural systems. (Straw) mulching is sometimes considered a crop residue management practice but is treated as a separate technique in this report.
Organic fertilisation	Organic fertilisation is the application to soils of plant or animal-derived materials containing organic forms of nutrients that microorganisms in the soil decompose, making them available for use by plants.

(Source: European Commission, Joint Research Centre 2023[5], Oenema et al, 2017)

The **potential of these practices lies in their positive effects on biodiversity, soil and water parameters or features which determine farm system resilience** (see Table 3). For instance, multiple studies have shown that no till or reduced till improves the soil structure (Devot et al, 2023), allowing for increased biological activity (e.g. earthworms, insects) and better water retention capacity. This results in soils that are healthier and less susceptible to compaction and erosion, and which will be able to support better yields in drought years, requiring lower levels of irrigation. Other practices increase the diversity of farming systems, be that crop, biological or landscape diversity. For instance, landscape elements such as hedges or buffer zones can mitigate the impact of extreme weather events (heatwaves, storms) or reduce soil erosion, notably through their shades, wind-breaking and runoff reduction potential (Altieri et al, 2015).

Table 2. Selected sustainable practices and their potential to increase resilience to climate change risks through effects on biodiversity, soil quality and water conservation

	Sustainable practices								
Potential effects	Mixed/ Inter-cropping	Agroforestry	Crop rotation	Landscape features	Cover/ catch crops	Reduced/ no tillage	Crop residue management	Mulching	Organic fertilisation
Soil Organic Matter (SOM) build up		■	■		■		■		■
Better nutrient cycling		■	■		■		■		
Soil cover	■	■	■	■	■	■	■	■	
Reduced evapotranspiration	■	■			■	■	■	■	
Run-off reduction	■	■	■	■	■		■	■	
Increased Water holding capacity		■		■	■		■	■	■
Better infiltration		■	■		■	■	■	■	

[5] European Commission, Joint Research Centre, 2023. "iMAP, Integrated Modelling platform for Agro-economic and resource Policy analysis - Tools to assess MS CAP strategic plans on environment and climate performance, https://wikis.ec.europa.eu/display/IMAP/IMAP+Home+page, version October 2023.

<table>
<tr><th colspan="10">Sustainable practices</th></tr>
<tr><th>Potential effects</th><th>Mixed/ Inter-cropping</th><th>Agroforestry</th><th>Crop rotation</th><th>Landscape features</th><th>Cover/ catch crops</th><th>Reduced/ no tillage</th><th>Crop residue management</th><th>Mulching</th><th>Organic fertilisation</th></tr>
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<tr><td>Lower soil compaction</td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td></td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td></td><td></td></tr>
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<tr><td>Better hydrological regulation</td><td></td><td></td><td></td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Higher water use efficiency</td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td></td><td></td><td style="background:#9bbb59"></td><td style="background:#9bbb59"></td><td></td><td></td></tr>
<tr><td>Stronger mycorrhizal network</td><td></td><td></td><td></td><td></td><td></td><td></td><td style="background:#9bbb59"></td><td></td><td style="background:#9bbb59"></td></tr>
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(Source: Altieri et al, 2015)

3. Wheat, potato, and olive production: climate change impacts and sustainable practices

The following sub-sections provide an overview of the production and consumption levels in the EU and highlights their importance for European food culture. For each of the three arable crops, we describe the main climate risks and impacts and review the available evidence on how different sustainable cropping practices affect key soil, water and biodiversity parameters and yields in European agro-environmental conditions.

3.1 Wheat

Wheat is **one of the world's main rain-fed crops** and constitutes one of the most important cereals for global food production. The cultivation of wheat dates back to the beginning of agriculture (8000 to 10,000 years ago) and continues to feed large parts of the world's population to this day (Venske et al, 2019).

Continuous improvements in wheat cultivation over multiple millennia, either intentionally or unintentionally, have contributed to the relative adaptability of wheat (Trnka et al, 2019). The large genetic diversity of wheat allows the crop to be grown in various climates, covering temperate, Mediterranean and subtropical regions (de Sousa et al, 2021). For example, Shewry (2018) notes that there are over **25,000 varieties** of *Triticum aestivum* L. that have been adapted to different environments. Wheat is cultivated in the two hemispheres, ranging from approximately 67° North to 45° South, while it is also suitable for a vast range of altitudes. However, this cereal crop is grown less in tropical areas. It is estimated that wheat is cultivated on **220 million hectares (ha)** around the world, which is the largest harvesting area of all crops (Venske et al, 2019). Wheat provides around **20% of all calories** consumed by humans globally and **total global trade in wheat equals** that of maize and rice combined (Trnka et al, 2019).

Hexaploid bread wheat (*Triticum aestivum* L.) and tetraploid durum wheat (*Triticum durum* Desf.) are the most common varieties of modern wheat cultivation (de Sousa et al, 2021). In general, common wheat is often milled into flour, which is subsequently used for many types of dishes around the world. Couscous, for instance, is widely consumed in many countries located in North Africa and is produced with wheat. In Italy, durum wheat is traditionally used to make different types of pasta. Durum wheat is also an integral part of the production process of breakfast cereal, as well as the noodles in kugel, which is a sweet pudding (de Sousa et al, 2021).

In many countries, wheat is used to produce bread. Different types of bread are made under varying processing conditions and require specific inputs, resulting in different bread characteristics. For example, wheat grains are used to manually or semi-mechanically produce typical French bread, as well as varying types of Arab flat bread. Soft wheat is typically used for the making of light dough suitable for Asian bread that is cooked with steam. Hard wheats, on the contrary, are more suitable for the production of rolls to be consumed with hamburgers and hot dogs. Other types of bread produced with wheat include Indian chapati and Mexican tortillas (de Sousa et al, 2021).

3.1.1 EU overview

The world's **leading wheat producers** include China, India, Russia and the United States, as well as France, Germany, Ukraine and Canada. **China** is the world's largest producer with 137,7 megatonnes (Mt) per year, followed by **India** with 107,7 Mt and **Russia** with 95,4 Mt. Total global wheat yields are estimated to be **803,0 Mt per year**. The vast majority of wheat production comes from soft wheat, while only a small amount is hard wheat at 33,0 Mt (Agreste, 2024)

In 2022, the European Union (EU) produced approximately **133,8 Mt** of wheat, representing **16,7% of global wheat yields**. This marks a 3.1% decline from the 138,1 Mt the year before. **France** is the largest producer of common wheat in the EU, and the fifth wheat producer in the world, with an annual production level of **33,7 Mt**. This is followed by Germany (22,4 Mt), Poland (13,1 Mt), Romania (9,1 Mt) and Bulgaria (6,4 Mt). Collectively, these five Member States grow **66,7%** of the EU's total common wheat production (Agreste, 2024).

3.1.2 Impact of climate change on wheat cultivation

Increasing global temperatures, changing rainfall patterns and climate hazards are projected to strongly affect global wheat production (Pequeno et al, 2021). The main climate hazards projected to impact wheat cultivation in Europe include rising CO_2 concentrations, extreme temperatures and heat, water stress, as well as heavy precipitation. Pests and plant diseases also constitute an important stress for wheat crops.

Increase in atmospheric CO_2 concentrations

Scientific literature shows that higher atmospheric CO_2 concentrations can **increase wheat yields**. Since pre-industrial times, CO_2 levels have risen from 280 to 415 µmol mol^{-1} (micromole) and are projected to reach 550–600 µmol mol^{-1} by 2050 (Helman and Bonfil, 2022). CO_2 fertilisation is expected to **positively affect biomass accumulation** in crops by increasing the photosynthesis rate, which is especially the case for C_3 grains such as wheat and sunflower[6] (EEA, 2019). The positive impact of CO_2 fertilisation on wheat crops is supported by Olesen (2016). The researchers confirm that elevated CO_2 concentrations are projected to induce yield increases, provided adequate water and nutrient availability for crops.

However, there is evidence suggesting that higher atmospheric CO_2 concentrations may have a **negative impact on the quality of wheat crops**. Increases in CO_2 levels have been found to lower grain protein content, which reduces the baking quality of wheat (Olesen, 2016). Wheat protein concentrations fell by as much as **9%** under CO_2-rich experiments conducted by Fernando et al (2015), whereas Högy et al (2013) observed a **7,9%** reduction in protein concentration under CO_2 enrichment. Furthermore, higher CO_2 levels have been associated with reductions in zinc and iron concentrations. Wheat crops cultivated under elevated CO_2 levels had **9.3% lower zinc** and **5.1% lower iron** contents, respectively (Myers et al, 2014). This demonstrates that changes in atmospheric CO_2 concentrations can alter the quality of wheat crops.

Moreover, it should be noted that CO_2 fertilisation, and changes in the baking quality of wheat, are not the only factors influencing wheat yield projections. In fact, Helman and Bonfil (2022) show that the negative impacts of warming and droughts are **expected to offset the benefits** of CO_2 fertilisation in many wheat-producing countries. The authors found that a CO_2 increase of 98 µmol mol^{-1} from

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[6] C3 plants are those whose method of photosynthesis is adapted to cooler and wetter climates. They represent the majority of plants globally and include rice, soybean, and wheat. C3 plants are less efficient at creating energy for growth than C4 type plants in hot and dry climates (https://tabledebates.org/glossary/c3-plants).

1961-2019 increased yields by **7%** in the top-twelve wheat growing countries but warming of 1.2°C combined with water depletion **lowered yields by 3%**. Germany and France witnessed a **net yield loss of 3.1% and no gain**, respectively of the analysed time period. Yields in China and in the wheat-growing areas of Russia, Ukraine and Kazakhstan would be **5.5% lower** than under current CO_2 levels. Climate hazards, such as extreme heat and droughts, therefore, need to be taken into account when evaluating the impacts of global warming on wheat cultivation.

Extreme temperatures and heat

Tolerance to high temperatures varies substantially across wheat cultivars and growth stages, but extreme heat has **resulted in wheat yield reductions**. Over a certain threshold, high temperatures **decrease the rate of photosynthesis**, especially during the anthesis stage, while it can also increase evapotranspiration (Mäkinen et al, 2018). High temperature stress can **impede plant growth**, the formation of grains and other metabolic processes, such as enzyme activation and protein synthesis (Lamba et al, 2023).

Moreover, the occurrence of high temperatures during the anthesis stage can hamper pollination, disrupt ovary development and **lead to a non-recoverable reduction in yields because of floret infertility** (Jacott and Boden, 2020). Such detrimental effects on grain yields are confirmed by Balla et al (2011), showing reduced grain yields per plant, lower kernel numbers and decreased 1000-kernel weight. In contrast, during the early reproductive stages extreme heat has been associated with suppressed spikelet development and inflorescence (Jacott and Boden, 2020). Higher-than-optimal temperatures affect respiration and photosynthesis rates, which increases the atmospheric demand for water. This **reduces the water use efficiency** of wheat crops (Zampieri et al, 2017).

Therefore, the sensitivity of wheat to high temperatures differs across stages and heat can induce various effects that hamper crop development. An analysis of 65 published studies that was conducted by Jacott and Boden (2020) revealed that optimum temperatures for wheat cultivation during the anthesis and grain-filling stages are **21.0 °C**, and **20.7 °C**, respectively. The **estimated maximum temperature** tolerated during the anthesis stage is **31 °C**, whereas tolerance during the grain-filling stage seems to be higher, namely **33.4–37.4 °C** (Mäkinen et al, 2018).

Temperatures above such critical thresholds can **drive significant wheat losses**. Balla et al (2011) found that heat stress led to **wheat yield reductions of 31%**, which was primarily attributed to decreased kernel weight and lower starch content. These negative effects on yields are confirmed by Mäkinen et al (2018), stating that wheat crops experience stresses around the heading above **31 °C**, reducing yields for **77% of the examined cultivars**. Some cultivars may respond positively to heat, but most suffer under extreme temperatures (Mäkinen et al, 2018). While heat stress affects wheat cultivars to varying degrees, depending on the length and intensity of high-temperature periods, it is generally considered that **extreme heat decreases final wheat yields** (Iqbal et al, 2017; Zampieri et al, 2017).

Drought

Studies show that droughts negatively affect wheat crops. Droughts, or water stress, have led to **reductions in wheat biomass production** resulting from lower grain yields and decreasing plant height (Zhang et al, 2018). Water stress **reduces photosynthesis**, which impedes crop growth, and hinders the provision of nutrients (Mäkinen et al, 2018).

The precise impacts depend on the development stage of the crop. Droughts impacting wheat during the early stages of its growth have been shown to negatively affect **germination, soil coverage** and **canopy establishment**. Impacts on soil coverage, in particular, can limit water availability, suppressing crop development (Mäkinen et al, 2018). Daryanto, Wang and Jacinthe (2016) found that water stress occurring during the vegetative phase causes wheat crops to give more assimilates to their roots, **reducing the number of leaves** per plant, plant **leaf size** and **leaf longevity**. Especially the combination of a **low photosynthetic sink** and a **decreasing nutrient uptake**, resulting from drought conditions, can have a strong detrimental effect on wheat (Daryanto, Wang and Jacinthe, 2016).

These effects have been found to **reduce wheat yields**. Based on a global synthesis of data from 144 different studies, performed by Daryanto, Wang and Jacinthe (2016), the authors demonstrate a **20.6% drop in wheat yields** under drought conditions. In the analysis conducted by Zhang et al (2018), wheat cultivation suffered from a similar **27.5% reduction in yields** when subject to drought. This was attributed to decreases in grain weight, panicle length, panicle number per plant and grain number per panicle. The detrimental effects of drought conditions on wheat yields were also supported by Matiu, Ankerst and Menzel (2017), albeit a significantly lower reduction in yields was found **at 4.4%**. From the reviewed studies, the largest decrease in yields was observed under Balla et al (2011), reporting **a 57% loss in wheat yields**. This shows that **wheat cultivation is sensitive to drought**, but the precise yield losses vary substantially. Different factors influence the severity of yield losses, such as the type of agro-ecosystem, the cultivars that are used, the timing, length and intensity of droughts, as well as the soil texture (Daryanto, Wang and Jacinthe, 2016).

Heavy precipitation and waterlogging

Extreme rainfall, inundation and insufficient water drainage can lead to **waterlogging**, which constitutes one of the primary abiotic stresses affecting crop productivity (Bailey-Serres and Voesenek, 2008). Waterlogging occurs when soil moisture levels exceed the field's capacity, saturating soil pores, profoundly altering soil properties. While water supply plays a crucial role in crop development, excessive rainfall or inundation can **severely harm the development of wheat crops** and their yields (Pais et al, 2022).

The effects of waterlogging on wheat cultivation depend on multiple factors, such as the duration and depth of waterlogging, the crop's development stage, and other weather conditions. Under normal circumstances, aeration enables O_2 intake and CO_2 output to ensure nutrient absorption and enable crop development (Morales-Olmedo, Ortiz and Sellés, 2015). In excess water conditions, on the contrary, **the availability of soil oxygen is reduced**. This impacts the absorption and transport of nutrients crucial for plant growth and yields, while it can also hamper root growth, and ultimately, cause root die-off (Herzog et al, 2016). Such changes in the soil can impede vegetative development and cause plant organ senescence. In addition, detrimental effects may include **reduced photosynthesis** and **CO_2 assimilation rates**, as well as **lower leaf water potential** and **nitrogen content** (Pais et al, 2022). Heavy precipitation has also been found to **increase soil erosion** and contribute to **nutrient leaching** (Mäkinen et al, 2018).

These negative effects can exert a profound impact on wheat yields. In fact, it is estimated that **10 to 15 million hectares** of wheat cultivation are affected by waterlogging around the world (Hossain and Uddin, 2011). This corresponds with annual global yield losses of **20-50% per year** (Pais et al, 2022). Dickin and Wright (2008) found that grain yields decreased by **20%** under waterlogging during a period of 44 days, while a **24%** decline in yields was observed resulting from waterlogged conditions for 58 days. Moreover, the severity of waterlogging strongly influences total yield losses. Under different degrees of waterlogging, including low, moderate and severe, Setter et al (2009) highlight a grain yield reduction of approximately **10%**, **25%** and **65%**, respectively. Reductions in wheat yields, ranging between **15-20%**, were also reported by Herzog et al (2016). These findings show that the impacts of waterlogging may vary but tend to decrease wheat yields.

Weeds, pests and plant diseases

There exist many types of weeds, pests and plant diseases that pose a threat to wheat cultivation. These include various weed species, obligate parasites, residue borne and non-obligate semi-biotrophic pathogens, soilborne pathogens, viruses and insects (Duveiller, Singh and Nicol, 2007). It is estimated that they are responsible for **21.5% of average annual wheat yield reductions** (Minter and Saunders, 2023).

Box 4. Climate hazards: the impact on French wheat cultivation

Climate hazards have already impacted wheat yields in France. Wheat yields fell substantially in **2003** and **2007** due to adverse weather conditions. In 2003, **heat** and **water stress** strongly affected wheat crops. Low soil moisture and higher-than-optimal soil temperatures were observed during the growing season of 2003. These unfavourable conditions, combined with substantial reductions in plant transpiration, decreased biomass production and reduced wheat yields in France (van der Velde et al, 2012). In 2007, on the contrary, lower wheat yields were attributed to a **wetter-than-average growing season**. Heavy rainfall led to excess moisture conditions that hampered wheat cultivation. Researchers argue this may have resulted from water lodging affecting grain formation and the development of harmful pests that favour wet growing conditions (van der Velde et al, 2012).

However, the most significant decline in French wheat production occurred in **2016**. National wheat yields fell by **27%**, leading to **2.3 billion $USD loss** in the trade balance of France (Nóia Júnior et al, 2023). This was largely caused by **compound events** negatively affecting wheat grain numbers and grain size. In particular, the combination of **low solar radiation** and **heavy precipitation** was found to harm grain numbers, whereas anoxia, fungal foliar disease and ear blight strongly impacted grain size (Nóia Júnior et al, 2023).

In the context of intensifying climate hazards, the development of pests and diseases has been linked to **excess water conditions**. High precipitation and excessive soil moisture tend to **favour pests and plant diseases** (van der Velde et al, 2012). This also pertains to **Septoria leaf blotch** (*Mycosphaerella graminicola*), which is one of the most common types of pathogens affecting wheat crops (van der Velde et al, 2012). In fact, pests and diseases have already contributed to recent losses in wheat yields. France suffered a severe decline in wheat production in 2016. **Fungal foliar diseases** and **ear blight** were responsible for **11%** and **10%** of grain yield loss, respectively (Nóia Júnior et al, 2023). The main diseases observed during the season, as reported by Nóia Júnior et al (2023), were **wheat fusarium ear blight** (*Microdochium nivale*), **leaf rust** (*Puccinia striiformis f. sp. tritici*) and **septoria leaf blotch** (*Zymoseptoria tritici*).

3.1.3 Cropping practices

As described above, different types of strategies can be employed to increase the resilience of crops to climate hazards. The sections below present some of the sustainable cropping practices that can help mitigate the negative impacts of climate hazards on wheat cultivation, and which are most frequently reported on in the literature. These include intercropping, agroforestry, no-tillage, and crop rotations.

Intercropping

Intercropping entails "cultivating two or more crop species or genotypes in the same area and coexisting for a time so that they interact agronomically" (European Commission, Joint Research Centre, 2023a). There exist various types of intercropping, such as row, mixed, strip or relay intercropping, each with distinct spatial and temporal attributes (Maitra et al, 2021). Intercropping has been practiced for a long time throughout history, including by ancient civilisations. While it is still used in developing countries, intercropping started to disappear in many parts of the world since the emergence of modern monocultures (Maitra et al, 2021). Nevertheless, cultivating different crop species simultaneously can deliver multiple benefits to help mitigate impacts from climate hazards. Wheat-based intercropping can have a positive impact on water use efficiency and erosion control, suppress weed and pests, and improve yields (Rebouh et al, 2023).

A considerable number of studies demonstrate that that intercropping can **improve water use efficiency**. Crops that are grown concurrently use the common pool of soil moisture. A combination of deep and shallow-rooted crops, in particular, can enhance the usage of available soil moisture. Under water deficit conditions, deep-rooted plants can help to bring water from deeper layers of the soil to the comparatively dryer upper layer, which benefits other crops unable to reach soil moisture from the deeper layers (Maitra et al, 2021). Hussain et al (2023) have found that intercropping can improve the water use efficiency of wheat crops. Under rainfed conditions, wheat and maize crops performed better when grown in an intercropped system than their respective monocrops (Hussain et al, 2023).

These findings are confirmed by Chai et al (2013) whose experiments resulted in a **25% increase in water use efficiency** for wheat-maize intercropping, as compared to sole wheat. Yin et al (2018) report a **45.7-48.3%** improvement in water use efficiency for wheat-maize intercropping (combined with reduced tillage and wheat straw residue retention) in comparison with conventional wheat monoculture. While this demonstrates the benefits for wheat-maize mixtures, wheat-chickpea intercropping has also shown to enhance water use efficiency (Aulakh, Singh and Walia, 2019). These results indicate that wheat-based intercropping can help improve water use efficiency, which is beneficial for wheat crops under water stress conditions.

Furthermore, intercropping can **reduce runoff** and **control soil erosion** (Khanal et al, 2021). The higher coverage of ground area tends to control topsoil erosion and limit the loss of nutrients (Maitra et al, 2021). For instance, the review from Aziz et al (2015) on wheat-based intercropping shows that combining wheat and potato grown in strips has resulted in **lower wind erosion**. Wheat-based intercropping systems have reduced wind erosion, as well as soil degradation and desertification. Erosion control could be enhanced by way of well-managed strip intercropping to increase soil and water conservation (Aziz et al, 2015).

Intercropping wheat has also been linked to **greater weed control**. Higher crop coverage in intercropping systems has contributed to the suppression of weeds (Maitra et al, 2021). Reduced weed infestation levels have been observed for various crop mixtures, including wheat-lentil (Aziz et al, 2015), wheat-faba bean (Eskandari and Ahmad, 2010), and wheat-chickpea intercropping (Maitra et al, 2021). These positive effects are thought to be linked to a **lower availability of environmental resources** for weeds (Eskandari 2011).

Moreover, findings indicate that wheat-based intercropping can greatly **reduce the prevalence of pests and diseases**, as compared to monocultures (Chevalier Mendes Lopes et al, 2016). This is frequently attributed to **associational resistance**, which implies the ecological interaction between plant species to reduce vulnerability to pests (Chadfield, Hartley and Redeker, 2022). For instance, host plant odours may be masked by the introduction of other non-host plants, disrupting the ability of pests to detect crops (Chevalier Mendes Lopes et al, 2016). Studies report positive impacts in the context of multiple different combinations of wheat intercropping. In an oilseed-wheat intercropped system, the presence of *Sitobion avenae* (an aphid) was greatly reduced, as compared to monoculture patterns (Wang et al, 2009). Wheat-winter rye intercropping has been found to decrease incidence of leaf fungal diseases, while a mixture of wheat and hop clover (*Madicago lupulina*) has reduced the prevalence of the plant disease caused by the fungus *Gaeumannomyces graminis* (Aziz et al, 2015).

Besides providing environmental benefits, intercropping can **increase wheat yields**. The reviewed literature indicates that intercropping systems can improve overall wheat yields as compared to monocultures (Rebouh et al, 2023). The comprehensive review of wheat-based intercropping conducted by Aziz et al (2015) shows that yield advantages in mixed cropping systems are attributable to **more efficient resource utilisation**, such as water, light and nutrients. Barillot et al (2014) also found that wheat-pea intercropping increased radiation use efficiency, while Zhang and Li (2003) observed higher nitrogen and phosphorus uptake in wheat-maize intercropping.

Increases in wheat yields were reported for different intercropping combinations, including wheat-maize, wheat-barley, wheat-pea and wheat-onion, among others (Aziz et al, 2015). Chai et al (2013) concluded that wheat-maize intercropping resulted in a **27% increase in grain yield** as compared to average yields of sole maize and wheat. Grain yields were also approximately **7-8% higher** in wheat-faba bean mixtures than in wheat monocultures (Kaci, Ouaret and Rahmoune, 2022). Therefore, intercropping has shown to result in greater wheat yields.

It should be noted that the delivery of these benefits depends on a variety of factors. These include aspects such as the **compatibility of crop species**, **crop maturity**, **time of planting** and **plant density** (Aziz et al, 2015). While crops of dissimilar growth patterns can help ensure complementarity to gain environmental benefits and yield improvements, inappropriate crop combinations may lead to higher inter-species competition for resources, such as water, light and nutrients (Maitra et al, 2021). For instance, Ebrahimi et al (2017) noted that wheat-rapeseed intercropping reduced wheat yields, because rapeseed dominated over the wheat crops that were grown. Other aspects pertain to the **wheat varieties** that are used, **soil characteristics** and the **environmental conditions** of the region (Rebouh et al, 2023). These parameters, including the compatibility of crop species and their suitability for different climates, need to be considered when adopting intercropping practices (Khanal et al, 2021).

Box 5. Wheat-faba bean intercropping in France

The **EU-funded ReMIX project** (2017-2021) examined how intercropping, or species mixtures, can increase the resilience of agricultural systems. By employing a multi-actor approach, the project delivered knowledge and practical solutions for farmers on the adoption of intercropping (European Commission, 2022). The project established 11 Multi Actor Platforms (MAPs) across **nine EU Member States** and **the United Kingdom**, constituting a network of experimental trials and on-farm demonstrations. One of these MAPs was located in **the southwest of France**, in the region of **Occitanie** (de Buck et al, 2021).

In this area in the southwest of France, farmers were the driving force behind the experimentation with different intercropping systems. The farmers tested various crop combinations, such as **wheat-faba bean**, **lentil-wheat** and **triticale-wheat-pea-faba bean**, but also barley-pea and lentil-barley, among others (Bedoussac et al, 2021). In Occitanie, where the experiments were held, average annual rainfall is 700-800 millimetres, while the average yearly minimum and maximum temperatures are 7.7 °C and 18.7 °C, respectively (de Buck et al, 2021).

In the wheat-faba bean mixture, sowing took place in November, whereas the harvest was in early July. The sowing and harvesting were done simultaneously for the two crops. Farmers grew wheat with the objective to **produce food for human consumption**, while the faba beans were cultivated for animal feed. The wheat and faba beans were sold separately to a cooperative (Bedoussac et al, 2021).

The farmers showed that wheat-faba bean intercropping provided multiple benefits. They concluded that the crop species mixture delivered a **good wheat protein content**, while the presence of rust on the faba beans was **lower** than in sole cropping. The farmers reported positive results for overall productivity; **a total yield of 3-3,5 tonnes per hectare** (t/ha), including **0,8-1 t/ha of faba bean**. Although, the farmers noted that **the mixing of species at sowing** and the **sorting at harvest posed a challenge**. Farmers also indicated that very high faba bean may dominate over short straw wheat (Bedoussac et al, 2021).

Lastly, it is important to note that there are other **economic considerations** and **limitations** associated with intercropping. Aziz et al (2015) report that various intercropping systems have led to **higher economic returns**. The authors show that wheat-potato and wheat-safflower improved economic returns, while a combination of wheat and sugarcane increased net income per ha, as compared to monocropping. However, intercropping can also pose challenges for the **practical management** of agronomic operations, which could **increase costs**. This is particularly acute when crops have dissimilar input requirements for water, fertilisers and plant protection (Maitra et al, 2021). Species mixtures may require **new equipment** for applying such inputs or **new machinery** for sowing and harvesting crops, separating grains post-harvest, or managing weeds (Khanal et al, 2021; Maitra et al, 2021).

Agroforestry

Agroforestry can be described as "a particular type of land-use system and technology where woody perennials (trees, shrubs, etc.) are deliberately used on the same land management unit as agricultural crops and/or animals" (European Commission, Joint Research Centre, 2023d). There exist different types of agroforestry practices, such as alley cropping, riparian forest buffers and silvopasture, each with unique approaches and benefits from combining trees and/or shrubs with crops or livestock (Schoeneberger et al, 2012). The term silvoarable agroforestry refers specifically to the integration of trees with crops (Arenas-Corraliza et al, 2019). While agroforestry is practiced all over the world, especially in tropical countries, agroforestry is not used extensively in Europe (Mosquera-Losada et al, 2018).

Agroforestry systems can protect crops against **the impacts of climate hazards**. Integrating trees in agricultural systems helps regulate local climates by providing **shelter from extreme temperatures** and **reducing water evaporation** from the soil surface (Jia et al, 2021). Trees provide shade to crops, which lowers air temperatures and can alleviate heat stress for crops (Quandt, Neufeldt and Gorman, 2023). Agroforestry has been proven to increase the resilience of wheat cultivation against climate hazards. For instance, Reyes et al (2021) show that an agroforestry system comprising wheat and walnut trees **reduced heat and drought-related stresses by 20-35%**. Medium-sized trees already started mitigating such climate hazards, but most plant stresses decreased in accordance with tree age (Reyes et al, 2021).

Woody vegetation can **protect crops against strong winds** and **reduce soil erosion**. Trees form windbreaks that provide shelter to crops during storms (Quandt, Neufeldt and Gorman, 2023). Vegetative elements acting as **windbreaks** reduce wind speeds and decrease erosion caused by wind (Brandle, Hodges and Zhou, 2004). In addition, placing trees adjacent to rivers helps to **moderate water flows**. This contributes to preventing soil erosion from strong river flows and can **reduce negative impacts from floods** (Quandt, Neufeldt and Gorman, 2023). In such situations, trees act as **water breaks** similar to the role of windbreaks in abating strong winds. Agroforestry also helps to enhance bank stability and can trap sediment (Schoeneberger et al, 2012).

Furthermore, agroforestry practices are generally considered beneficial for **soil water distribution** and **nutrient access**. While the relationships between tree cover and water supply are complex, tree components are often found to **reduce runoff** (Bayala and Prieto, 2020). Moderate tree cover has been found to increase infiltrability, enhancing groundwater recharge (Bayala and Prieto, 2020; Ilstedt et al, 2016). Deep-rooted trees, especially, allow for better access to water and nutrients in periods of drought. If trees are appropriately integrated in agricultural ecosystems, they can extract resources that would otherwise be lost (Schoeneberger et al, 2012).

The meta-analysis conducted by Torralba et al (2016) also reports these positive effects. The structural and functional complexity of agroforestry systems induces a **tighter coupling of nutrient cycles**, positively impacting nutrient concentration levels and soil fertility (Torralba et al, 2016). Agroforestry can help **increase the availability of nitrogen** by controlling leaching, which reduces the risk of nitrogen deficiency (Reyes et al, 2021). However, the precise effects are context-dependent and vary depending on different factors, such as the type of agroforestry system, tree and crop species, as well as pedoclimatic conditions (Torralba et al, 2016).

While agroforestry can provide environmental benefits to mitigate the impacts of climate hazards, integrating trees with crops has resulted in **both positive and negative impacts** on crop yields. As demonstrated by Jia et al (2021), reductions in light intensity due to tree cover can **decrease photosynthetic rates** and **grain yields in wheat**. Decreased light intensity significantly lowered the number of fertile florets per spike, which resulted in fewer grains. Nitrogen concentrations, protein and gluten contents increased, but **did not compensate** for the fall in wheat grain yields (Jia et al, 2021). These effects on wheat productivity are supported by Artru et al (2017), revealing that shading contributed to a decrease in grain yield, which was partially offset by higher grain protein content. This demonstrates that agroforestry affects both grain quantity and quality.

In addition, the presence of trees and crops on the same agricultural plot can **increase competition for water** and **nutrients**. This is particularly acute if crops and trees have overlapping root systems and/or similar temporal patterns of water demand (Reyes et al, 2021). These detrimental effects have also been reported for wheat cultivation. The yields of wheat crops grown on the same agroforestry plot as walnut trees had **fallen by 16%**, as compared to wheat monocultures. It should however be noted that this reduction was solely observed **20 years** after planting the walnut trees (Reyes et al, 2021).

Although, these negative effects are contradicted by other studies. Agroforestry has also been linked to **improvements in wheat yields**. For instance, Arenas-Corraliza et al (2019) revealed that wheat yields improved by **19%** in a cereal crop shading experiment, while a study from Thevathasan and Gordon (2004) found that wheat yields in agroforestry systems **are higher**, **or at least equal to**, sole cropping under drought conditions. Moreover, agroforestry has managed to **improve the stability of wheat yields**. The results from Reyes et al (2021) show a reduction in crop yields 20 years after tree planting, but indicate that walnut trees helped **alleviate biophysical stresses**. The trees mitigated extreme temperatures, nitrogen scarcity and water stresses, which ensured the **stability of yields** and **limited the overall decrease in crop yields** (Reyes et al, 2021). This shows that agroforestry can help to make wheat cultivation more resilient against climate hazards, but local circumstances must be considered to ensure the optimal delivery of its benefits.

Nonetheless, challenges persist to the adoption of agroforestry practices. Sollen-Norrlin, Ghaley and Rintoul (2020) find that **high costs** are commonly attributed to the implementation of agroforestry. The authors note that agroforestry is **labour-intensive**, which can deter farmers from transitioning towards agroforestry systems because of the costs associated with the high labour requirements. Furthermore, the improper management of agroforestry systems can increase competition between field components, as described earlier, which can induce financial risks because of lower yields (Reyes et al, 2021; Sollen-Norrlin, Ghaley and Rintoul, 2020). One of the key challenges is therefore to ensure that **adequate knowledge** is available on the suitability of specific crop-tree combinations adapted to the local climatic conditions (Mosquera-Losada et al, 2023).

Box 6. Agroforestry in Montpellier (Hérault, France)

Montpellier is a city located in the south of France at 10 kilometres from the Mediterranean Sea. The area has a Mediterranean climate with very warm and dry summers. Yearly rainfall is approximately 660 millimetres with the highest level of precipitation in fall and winter. Mean temperatures are around 7.1 °C in January and 23.4 °C in July. However, climate change is expected to strongly impact agriculture in Montpellier. Heatwaves and droughts, in particular, are projected to occur more frequently in the region (Climate-ADAPT, 2023).

Agroforestry practices have been adopted in Montpellier with the objective of making agriculture more resilient against climate hazards. An agroforestry scheme was implemented through the **EU-funded SAFE project**, which brought together researchers and end-users in the farm and forestry sectors (European Commission, 2023).

In Montpellier, the agroforestry system included a **mixture of wheat crops** and **walnut trees**. The researchers from the Institut National de la Recherche Agronomique (INRA) found a significant increase in productivity on the agroforestry plot. The results of the project show a **40% increase in productivity**. This implies that one hectare of walnut-wheat agroforestry equals the productivity of around 1.4 hectares where crops and trees are separated. Such productivity gains were realised with an optimal tree density of 50 to 100 per hectare while ensuring the adequate management of the agroforestry system, including the orientation of the tree line, the pruning regime and the cultivation of winter crops (Dupraz and Liagre, 2008).

While this case study demonstrates the positive impact of agroforestry on yields, trees also provide shelter to the crops from wind, rain and extreme heat. Moreover, trees tend to grow faster in the agroforestry system, as compared to an exclusively forestry plot. Nevertheless, the transition to agroforestry remains a long-term endeavour. To support planting half a million hectares of agroforestry, a 25-year national scheme has been implemented in France, based on the results obtained by INRA (Dupraz and Liagre, 2008).

No-tillage

Tillage serves to loosen and aerate the soil, which helps to increase soil porosity, improve water storage and promote crop root extension (Wang, 2014). Furthermore, tillage incorporates crop residues into the soil to enhance organic matter content and it plays a role in managing soil temperature (Rebouh et al, 2023). Tillage also changes soil structure, bulk density and pore size distribution (Wang, 2014).

There exist various types of tillage, such as **conventional tillage** (CT), **minimal tillage** (MT) and **no-tillage** (NT) (Gandía et al, 2021). The latter two are also commonly referred to as **conservation tillage** (Ruisi et al, 2014). No-tillage (or zero tillage) can be described as "a minimum tillage practice in which the crop is sown directly into soil not tilled since the harvest of the previous crop" (European Commission, Joint Research Centre, 2023b). Practicing no-tillage has been found to deliver environmental benefits that can help agricultural systems adapt to climate hazards. These include enhanced water retention, improved soil structure and organic matter, as well as higher wheat yields.

No-tillage has been found to positively affect **soil water retention**. De Vita et al (2007) report positive effects of NT on wheat grown under limited rainfall conditions. NT managed to enhance soil water availability due to **reduced soil water evaporation**. The use of NT delivered higher yields than CT under limited precipitation, whereas CT improved yields when rainfall was higher (De Vita et al, 2007; Ruisi et al, 2014). Ali et al (2019) examined the response of wheat-faba bean rotations to different tillage practices in dry areas. The authors also found that NT improved water retention when water availability was limited.

Multiple factors have been attributed to the positive effects of NT on wheat that is cultivated under water stress conditions. NT induces **changes in soil porosity** by increasing the number of small soil pores and reducing large pores. This **enhances the hydraulic characteristics of soils**, including water storage, infiltration, transport and drainage (Ruisi et al, 2014). Gandía et al (2021) confirm that NT holds significant potential for water soil storage to dampen the detrimental effects of climate hazards. Employing NT can preserve water from rainfall and increase soil water storage (Gandía et al, 2021;

Toliver et al, 2012). These positive effects are also supported by Liu et al (2021), showing that NT can improve soil water storage over CT to **facilitate water infiltration** and **soil moisture content**.

In addition, NT can **enhance soil organic matter**, **conserve nutrients** and **reduce erosion** (Ruisi et al, 2014; Tilman et al, 2002). In various experiments with maize and wheat, Liu et al (2021) report that NT increased soil organic matter as compared to CT. NT managed to increase soil organic matter by **36.4%** at the 0-10 cm soil layer, and by **31.1%** at the 10-20 cm layer. The total concentration of nitrogen was also markedly higher under NT, since a **68.5% increase** was observed in contrast to CT. The NT system **reduced soil disturbance** and **mechanical compaction**, while slowing down the degradation of soil nutrients (Liu et al, 2021).

The results from Ali et al (2019) show that NT combined with wheat-faba bean rotations **improved soil organic matter content** over CT, especially in the top 60 cm of the soil. (Krauss et al, 2022) found that reduced tillage increased soil organic carbon in the topsoil (0-10/15 cm), but decreased the soil organic carbon in the deeper soil layers (15/20-50 cm). The researchers also confirm that enhanced soil organic carbon in the topsoil contributes to **soil erosion control**.

NT holds significant potential to **maintain yields under extreme climatic conditions**. The beneficial effects of NT on soil moisture and organic matter can mitigate the impacts of extreme temperatures and water stress on wheat yields (Rebouh et al, 2023). The research conducted by De Vita et al (2007) shows that **NT** helps wheat attain **higher yields under water stress conditions**, whereas CT brings higher yields when water availability is sufficient. The higher yields from NT were attributed to **lower soil water evaporation** and **enhanced soil water availability**. These findings are consistent with Djouadi et al (2021). In dry conditions, NT provided significantly better wheat yields than CT due to enhanced water storage. On the contrary, when precipitation was higher NT and CT delivered similar wheat yields (Djouadi et al, 2021).

These findings underline the context-specificity of NT practices. While NT can deliver multiple environmental benefits, such as **enhanced water retention** and **higher soil organic matter**, NT tends to perform better **under dry conditions**. The selection of suitable tillage practices therefore depends on **the soil** and

environmental conditions (Rebouh et al, 2023). Additionally, there are economic factors that are relevant for deciding which tillage system to adopt. While little comprehensive research has been undertaken on the economics of NT, various aspects can influence the attractiveness of tillage practices. Brennan et al (2012) note that these include crop yields, machinery costs, labour and fuel costs, as well as the size of the farm, among others. These factors need to be carefully weighed in determining the suitability of tillage practices.

Crop rotations

Crop rotation refers to "the practice of alternating crops grown on a specific field in a planned pattern or sequence in successive crop years, so that crops of the same species are not grown without interruption on the same field" (European Commission, Joint Research Centre, 2023c). Rotations can vary from 2 to 3 years or be extended for an even longer period (Selim, 2019). Crop rotations can contribute significantly to improving wheat yields and deliver environmental benefits, including soil health, pest and disease regulation, as well as weed control (Rebouh et al, 2023).

Planting crops in rotation can be beneficial for **different soil parameters**. Crop rotations can enhance the **diversity of microbial communities**. It can help to enhance nutrient cycling, minimise erosion and increase carbon sequestration (Rebouh et al, 2023). Marini et al (2020) also found that rotations contribute to enhanced soil biota and improved soil fertility. This can be linked to a higher quality and chemical diversity of residues, which benefits soil fertility and organic matter. Zou et al (2023) conducted experiments with three rotation systems to examine benefits for the soil. These rotations included wheat-maize, wheat-peanut, as well as wheat rotated with both maize and peanut. Rotating wheat with maize and peanuts proved **beneficial to microbial biomass carbon** and enhanced the pool of soil organic carbon. This diverse cropping pattern also provided **higher wheat yields** than in wheat-maize (Zou et al, 2023). Moreover, wheat-based rotations can improve nutrient concentrations. Bezabeh et al (2022) show that wheat-faba bean rotations had higher **wheat grain nitrogen** and **protein contents**, which was attributed to nitrogen fixation carried out by the faba beans. The wheat-faba bean rotation also improved sulphur uptake and transportation to grains (Bezabeh et al, 2022).

Furthermore, crop rotations can help **reduce the prevalence of pests and diseases** by influencing the detection of host plants. Since arthropod pests depend on chemical and visual signals for choosing host plants, the introduction of crop rotations can **disrupt such cues**, which can help manage pests more effectively (Rebouh et al, 2023). Jalli et al (2021) found that wheat crop rotations **reduced the severity of leaf blotch disease**. The authors note that pest suppression was strongest in their most diverse crop rotation comprising wheat, turnip rape, barley and pea (Jalli et al, 2021).

Wheat-based rotations have also proven to **suppress fusarium crown rot**. Theron et al (2023) found that rotating wheat crops, in combination with non-host crops and suitable tillage techniques, decreased both the incidence and severity of the rot. Over a two-year period, wheat grown in rotations with annual medics, canola and lupin reduced fusarium crown rot while simultaneously increasing grain yield and quality (Theron et al, 2023). Incorporating *Brassica carinata* as break crops for wheat cultivation has also been proven to suppress fungi. Campanella et al (2020) show that the use of *Brassica carinata* resulted in an average reduction of 82% in the fungal plant pathogen *Fusarium culmorum*.

In addition, scientific literature has provided evidence on the benefits of crop rotation for **weed control**. Some crops can enhance weed control and limit competition between wheat and weeds for resources, such as sunlight, nutrients and water (Rebouh et al, 2023). Minhas et al (2023) show that sorghum-wheat rotations can strongly reduce weed infestation, resulting in lower weed density and weed biomass than under a fallow-wheat cropping system. Adding allelopathic crops to the agricultural plot, such as sorghum, was found to impede the establishment of weed flora. Integrating such crops in rotations helps disrupt weed cycles and reduces their growth (Minhas et al, 2023).

The positive effects of crop rotations on weed infestation are supported by Shahzad et al (2021). The researchers held experiments with five different crop rotations, namely sorghum-wheat, rice-wheat, cotton-wheat, mungbean-wheat and fallow-wheat. The lowest weed presence was found under the sorghum-wheat and cotton-wheat rotations, while weed infestation was highest in the case of fallow-wheat. It should be noted, however, that certain crop rotations may induce impacts on other parameters besides weed suppression. Shahzad et al

(2021) show that sorghum-wheat resulted in a lower prevalence of weed, but also reduced overall yields.

Nevertheless, multiple studies have reported that crop rotations have a **positive impact on wheat yields** and **quality**. Rotations of wheat and chickpea, comprising one year of chickpea crops followed by two years of wheat cultivation, were found to substantially increase wheat yields. While continuous wheat cropping produced mean yields of **5 t/ha^{-1}**, wheat-chickpea rotations resulted in yields of **5.8 t/ha^{-1}** and **5.5 t/ha^{-1}** during the first and second year after chickpea was cultivated (Lago-Olveira et al, 2023). Wheat rotation with faba beans has also been found to induce positive effects. Bezabeh et al (2022) reported that wheat-faba bean rotations increased both **wheat grain yield** and **nutrient concentrations** as compared to continuous wheat cultivation. Marini et al (2020) also found that crop rotations lowered yield losses from climate hazards, especially under drought conditions.

The research conducted by Mesfin et al (2023) highlights that multiple legume-wheat rotations have the potential to increase wheat productivity. These cropping systems included faba bean, dekeko, field pea and lentil, which improved wheat grain yields by **71.1%**, **52.3%**, **40.6%** and **34,5%**, respectively (Mesfin et al, 2023). The legumes improved nitrogen uptake of the subsequent wheat crops by increasing soil N concentration through biological nitrogen fixation.

This shows that rotations can **improve wheat yields** and **provide insurance by increasing crop diversity** (Marini et al, 2020). Lago-Olveira et al (2023) demonstrate that wheat-chickpea rotations can improve both **the environmental** and **economic performance** of the agricultural system. Incorporating chickpea in the rotations **improved the overall income per hectare** due to the lower cost of cropping chickea. Rebolledo-Leiva et al (2022) found that rotations including lupin, wheat and oilseed rape, as well as lupin, potato and wheat, increased profits by **19%** and **51%**, respectively.

While crop rotations can provide multiple benefits, it should be considered that shifting from monocultures to diverse rotations comes with limitations. The **choice of crops**, the **soil characteristics** of the field, **local weather conditions** and the **types of pests** and **plant diseases** prevalent in the region can strongly alter the suitability of crop rotation regimes (Rebouh et al, 2023). **Investments** may also be required to ensure the agronomic management of diverse crop rotations. These include, for instance, new machinery for processing and distributing crop species, or knowledge-sharing arrangements (Marini et al, 2020). These need to be taken into account to maximise the benefits of wheat-based crop rotations.

Box 7. Key messages

Wheat is a key crop for both production and consumption in the EU. The EU produces 16,7% of global wheat yields. Wheat (flour) is used to prepare many key 'ingredients' of many European cuisines such as baguette in France or pasta in Italy.

Whilst CO_2 fertilisation can positively impact biomass accumulation in wheat crops, higher atmospheric CO_2 concentrations may reduce the baking quality of wheat and lower grain protein content. Moreover, the impacts heat, drought and heavy rain might offset positive effects from CO_2 fertilisation. **Extreme heat** can lower photosynthesis, increase atmospheric demand for water and hamper the formation of grains. **Droughts** have been found to decrease biomass production, impede the provision of nutrients, and reduce water use efficiency. **Heavy rainfall** and waterlogging can reduce photosynthesis, obstruct vegetative development, increase nutrient leaching and may increase the development of pests and diseases.

Practices that can provide environmental benefits to mitigate the negative impacts of climate hazards include: **Intercropping** can help to improve water use efficiency, control soil erosion and enhance the suppression of weeds, pests and diseases. **Agroforestry** provides shelter to crops from extreme heat, can improve soil water distribution and reduces the negative impacts from floods. **No-tillage** has been associated with greater soil water retention and soil organic matter, as well as nutrient conservation and lower soil erosion. **Crop rotations** can also positively impact soil organic carbon and nutrient cycling and proves particularly beneficial for reducing the prevalence of weeds, pests and diseases. Scientific literature shows that the reviewed practices hold significant **potential for maintaining, or in some cases, even improving wheat yields**, as compared to conventional monocropping. Wheat crops are better able to withstand the negative impacts of hazards, such as heat stress, drought, or pests.

The delivery of environmental benefits depends on a wide variety of factors and is context specific. Therefore, **the local circumstances** need to be considered to ensure the suitability of sustainable practices. Multiple barriers impede the adoption of sustainable agricultural practices. Intercropping or no-tillage, for instance, may require **investments in new machinery or equipment**, constituting significant upfront costs for farmers. Furthermore, farmers may not have **the knowledge** that is necessary to make suitable agronomic management decisions. Guaranteeing that farmers have this knowledge is crucial, since it can strongly influence the environmental and economic outcomes of adopting sustainable farming practices. Agroforestry may also increase **labour costs**.

3.2 Potatoes

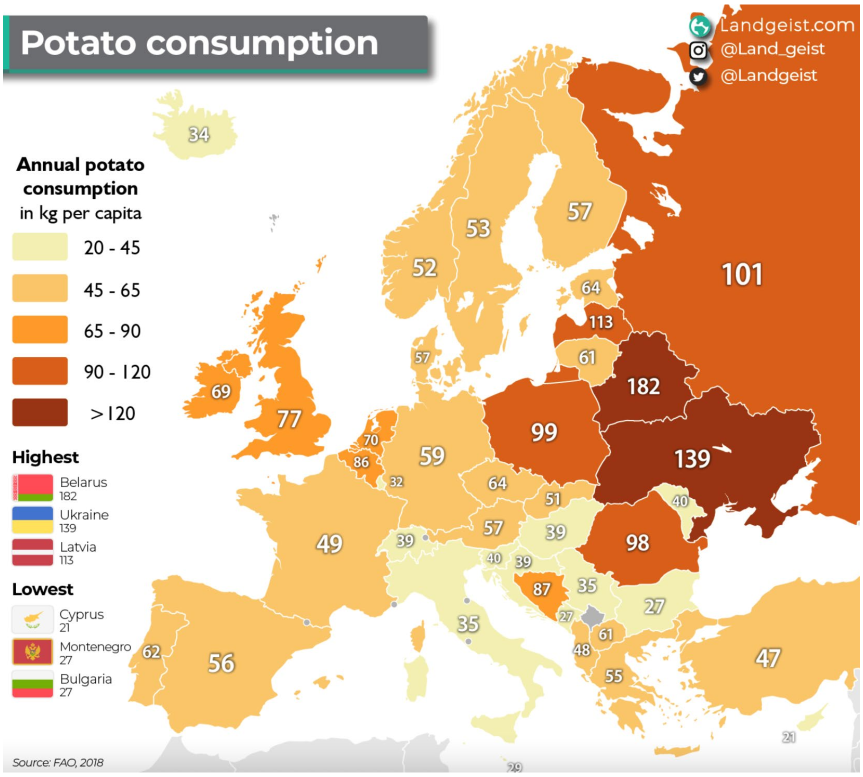
German Kartoffelklöße, Polish Pierogi, Belgian frites, French Pommes Duchesse, Italian gnocchi, Spanish Patatas bravas - Europe's eating habits would be very different had Christopher Columbus not made landfall in the Bahamas in 1492 in his attempt to find a direct route west from Europe to Asia. When Columbus stumbled upon the Americas, he lay the groundwork for the colonisation by the Spanish of much of the Americas and the discovery and introduction of New World Foods to Europe. It is widely assumed that Francisco Pizarro's men encountered potatoes as early as 1531 during their conquest of the Inca Empire and transported them back to Europe (MLUK 2023). At first, the vegetable was not widely accepted, and it took until the 18th century with its many wars and famines to make potatoes a staple food due to the relative ease of cultivating the crop, its suitability to various climates and its long shelf life (the low countries, 2021).

> "The most excellent gift that the old world received from America, the crown of all new agricultural plants, is without any doubt the potato; its cultivation in Europe is of world-historical interest."[7]

Today, it is impossible to imagine European cuisine without potatoes. Europeans top the table of potato consumers worldwide, and potatoes are an important dietary staple, especially in Eastern, Central, and Northwestern Europe (see Figure 1). On average, **each European eats 90kg of potatoes/year** (The Copernicus Programme, 2023b).

[7] Volz, K.W., 1852, p. 239f. Translated from German.

Figure 3.Annual potato consumption per capita in Europe (2018 data)



(Image: Landgeist, 2021)

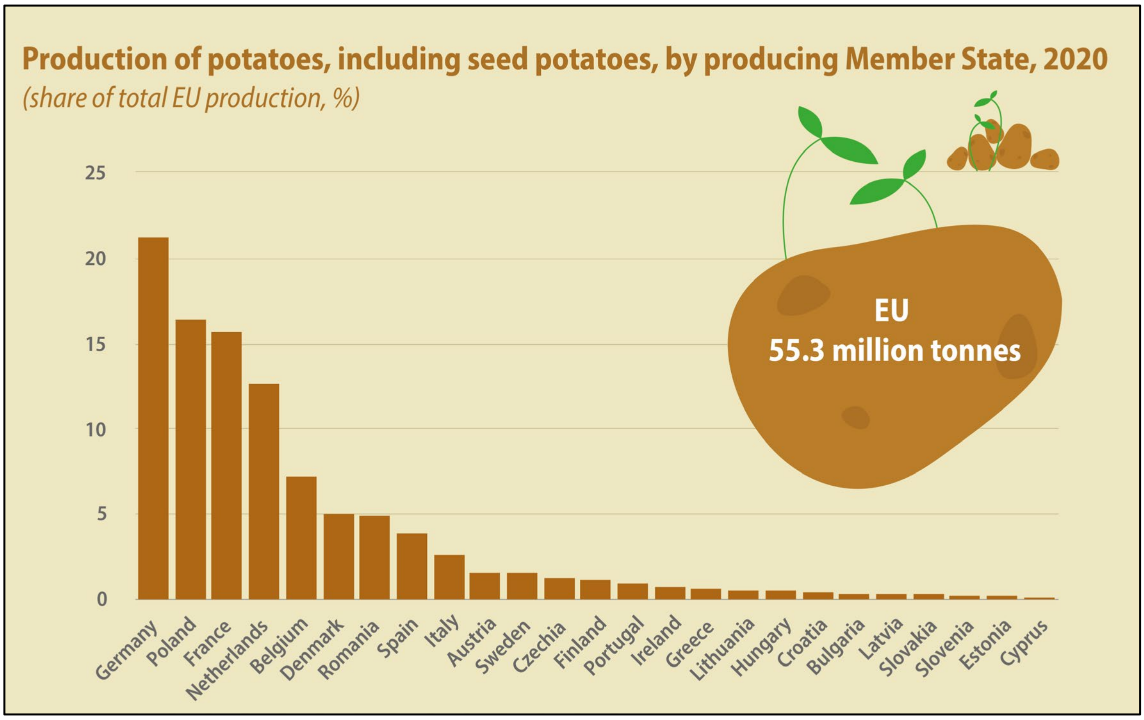
3.2.1 EU overview

Potatoes are **the world's largest non-grain food commodity, and the fourth most important staple food[8] overall after rice, wheat, and maize** (Ezekiel et al. 2013). As a low-fat food, rich in protein, starch, minerals, and vitamins and with a caloric density higher than any other commercial crop, it plays a key role in global food security (Ávila-Valdés et al. 2020; Lynn 2022). In 2022, more than 376 million tons of potatoes were produced worldwide[9]. Although grown on only around 1.7% of its arable land, the **EU is the second largest producer globally, accounting for around 37% of total production.** In 2020, around 55.3 million tons of potatoes were harvested across Europe (EU-27)· That year, potato production generated an estimated value of EUR 12 billion, representing 3.1% of the total value of EU agricultural output. The biggest potato producers in the EU are Germany (21.2%) Poland (16.4%), France (15.7%), the Netherlands (12.7), and

[8] A staple food is a regular part of a diet, constituting a dominant part of a diet and supplying a major proportion of energy and nutrient needs (https://www.fao.org/3/u8480e/u8480e07.htm)
[9] https://www.fao.org/faostat/en/#data

Belgium (7.2%). Together, they accounted for almost three quarters of the EU's harvested production of potatoes in 2020 (Eurostat, 2021).

Figure 4. EU production of potatoes broken down by EU Member State (share of total EU production in %)



(Image: Eurostat, 2021)

3.2.2 Impact of climate change on potato cultivation

Potatoes are mainly grown for their tubers (Dahal et al, 2019). As the main plant grows, the leaves produce sucrose through photosynthesis which is then transferred to the end of its underground stems (or stolons) and converted to starch. The stems thicken to produce up to 20 tubers, or potatoes. Once the plant dies at the end of the growing season, the tubers remain in the ground over winter, allowing the plant to produce new shoots the following year (FAO, 2009). Any stresses that have negative effects on these processes, such as extreme heat or drought, may substantially inhibit tuberization and tuber growth resulting in for example a decrease in tuber numbers and size, physical malformations, and premature plant death (Dahal et al, 2019; Lynn, 2022). As will be explained in the remainder of this section, traditional potato cultivation practices (see Box 5) might intensify these negative effects.

Box 8. Traditional potation cultivation practices in Europe

Potatoes are commonly grown on mounds or ridges in Europe, and much of the rest of the world (Reay, 2019). This technique ensures that the soil is well drained and aerated. The elevated ridges more effectively catch sunlight leading to warmers soil in the colder spring months thus promoting faster root and tuber development (Goffaert et al, 2022; Nerinckx, 2021). In four out of the five main European potato producing countries (Germany, France, the Netherlands, and the UK), 40 to 60% of the potato-cropped area is irrigated. The exemption is Belgium where 95% of its potato cultivation area is rain-fed (Goffaert et al, 2022). Potatoes are vulnerable to a host of pests, such as the Colorado potato beetle, aphids, wireworms, slugs, and nematodes, as well as bacterial, fungal, and viral diseases. diseases. To prevent the build-up of weeds and pathogens in the soil, potatoes are typically grown in rotations of three or more years, often alternating with maize, cereals, sugar beet, rape seed and vegetables (Goffaert et al, 2022). However, many pests and diseases are still mostly fought with chemicals. Late blight (Phytophthora infestans) for example, one of the main threats to potatoes, requires between 10 and 20 applications of fungicides over the growing season (Vincent et al, 2013).

Figure 5. Potatoes cultivated on ridges

(Image by Richard Webb)

Higher atmospheric CO_2 concentrations

Hijmans (2003), assessing the impacts of increasing temperatures on yields, concluded that world **potato production could decline by 18% to 32% (without adaptation) and by 9% to 18% (with adaptation)**[10] **for the period 2040-2069.** The study, however, did not consider the effects of atmospheric CO_2 concentrations. Experimental studies show that **potatoes might benefit from**

[10] Adaptation measures considered included changing planting times and using cultivars better adapted to warmer temperatures.

increased CO_2 concentrations in the atmosphere (see Dahal et al, 2019 for an overview). A possible reason for this increase could be an increase in photosynthetic rates which in turn leads to higher growth rates and more starch being transferred to the plant's stolon. In addition, increased atmospheric CO_2 concentrations leads to lower water losses from transpiration as leaves need to open their pores (stomata) less to take up the CO_2 amounts needed for photosynthesis. (Dahal et al, 2019; Lynn 2022). However, as Dahal et al (2019) note, most experiments to date were conducted under ambient temperature with no water limitations. Given that the predicted rise in atmospheric CO_2 is expected to be coupled with an increase in temperature, the yield gain achieved through high CO_2 may be offset by yield losses due to other abiotic and biotic stressors.

Increasing temperatures

The potato plant is a temperate climate crop but is grown all over the world in a range of climatic conditions (FAO, 2009). However, potatoes develop best at temperatures around 18-20°C, cool nights (15-18°C), and with adequate water supply (Ávila-Valdés et al, 2020; Handayani et al, 2019; Goffaert et al, 2022). **Temperatures above 30°C during growing season can have a range of negative effects on the development of the potato plant and the development of its tuber** (Obidiegwu et al., 2015; Nerinckx, 2021; Adekanmbi et al, 2024; Aien et al, 2016):

- Delayed root emergence, and growth, especially if exposed to high temperature from the beginning of the growing period.
- Reduced number of stolons and tubers.
- Slower tuber growth and smaller size.
- Physiological damage to tubers, such as hollow heart, tuber cracking, secondary growth, malformations, and skin russeting
- Early sprouting of tubers.

Moreover, temperature rises affect the above- and below parts of the plant in different ways. The plant develops well in temperatures of 20–25◦C while below ground, 15–20◦C are ideal (Dahal et al (2019). According to Dahal et al (2019), air temperatures above 25C have been found to delay tuberization, and below ground, tuber initiation and bulking is already delayed at soil temperatures above 18°C. These **effects are likely to be exacerbated by the in Europe typical ridge cultivation** which warm up more quickly than flat soils (see Box 5). In warmer months, this cultivation technique can lead to heat stress (Nerinckx, 2021).

Reduction in annual precipitation

Potatoes require 500 mm to 700 mm of precipitation to fully develop (Goffaert et al, 2022). **They are extremely sensitive to water deficits**, particularly during the tuberization and bulking stages, due to a shallow root system (Dahal et al, 2019, Handayani et al, 2019). A water deficit during the tuberization stage can lead to a reduction of the total leaf area resulting in a lower number of tubers developing. Ridge planting tends to dry out soils faster than level soil due to their height and the larger surface area. Coupled with the shallow roots, potato plants are at risk of shedding their leaves and water stress. (FAO, 2009). Water stress during the later tuber bulking stage can affect tuber size and quality by decreasing transpiration rate (reduction of stomatal conductance), and photosynthesis rate per unit of leaf area (Avila-Valdes et al, 2020). Physiological defects are more likely to appear and there is a change of a considerably increase in glycoalkaloids (solanine and chaconine), toxic compounds that can cause gastrointestinal and neurological symptoms when consumed (Dahal et al, 2019).

Frequent heavy rainfall events

Excessive water on or around potato plants during growing season negatively impacts tuber development. A **waterlogged soil prevents oxygen exchange, leading to diminished root growth** (Alva, 2008), and the **decaying of the inner potato tissue**. A so-called 'black heart' forms, a circle of dead tissue at the centre of the tuber potato tubers (Geddes, 2017). In addition, heavy rainfall can lead to water pooling between ridges and subsequent rapid flows of water from the field causing surface water contamination by plant protection products and nutrients (e.g. nitrates) (Nerinckx, 2021; Devaux et al, 2021). Flooded fields may also disrupt planting and harvesting operations, and lead to yield losses as potatoes which are inundated for more than 24 hours start to rot. For instance, heavy rainfall in October and November of 2023 made harvesting impossible in some areas of Belgium (Potatoes without borders, 2023). A study of key weather extremes affecting potato production in the Netherlands concluded that, over the last 60 years, the wet start or wet end of the growing season had had the highest negative impact on potato yields (van Oort et al, 2012).

Pest and diseases

Potato is **susceptible to a wide range of pests and pathogenic organisms which can cause severe quality and yield losses**. Some of the most important diseases worldwide are late blight (Phytophthora infestans), potato virus Y (PVY), and yellow potato cyst nematode (Globodera rostochiensis) (Vilvert et al, 2022). Climate hazards may disrupt the potato plants' natural defense mechanisms. For example, potato plants produce substances to protect themselves from nematodes, of which some can cause a 75 % loss in potato yields (Seinhorst, 1982), by exchanging information via the mycorrhiza network. This triggers an immune response which allows the plant to release substances that destroy the nematodes. Hence, it is crucial not to disturb the soil too often as this can damage these mycorrhizal connections (Berényi Üveges et al, 2020). Further, temperature and other changes might lead to more favourable conditions for some pests and the migration of beneficial organisms from warmer to colder climates (George et al. 2017, Adekanmbi et al, 2024).

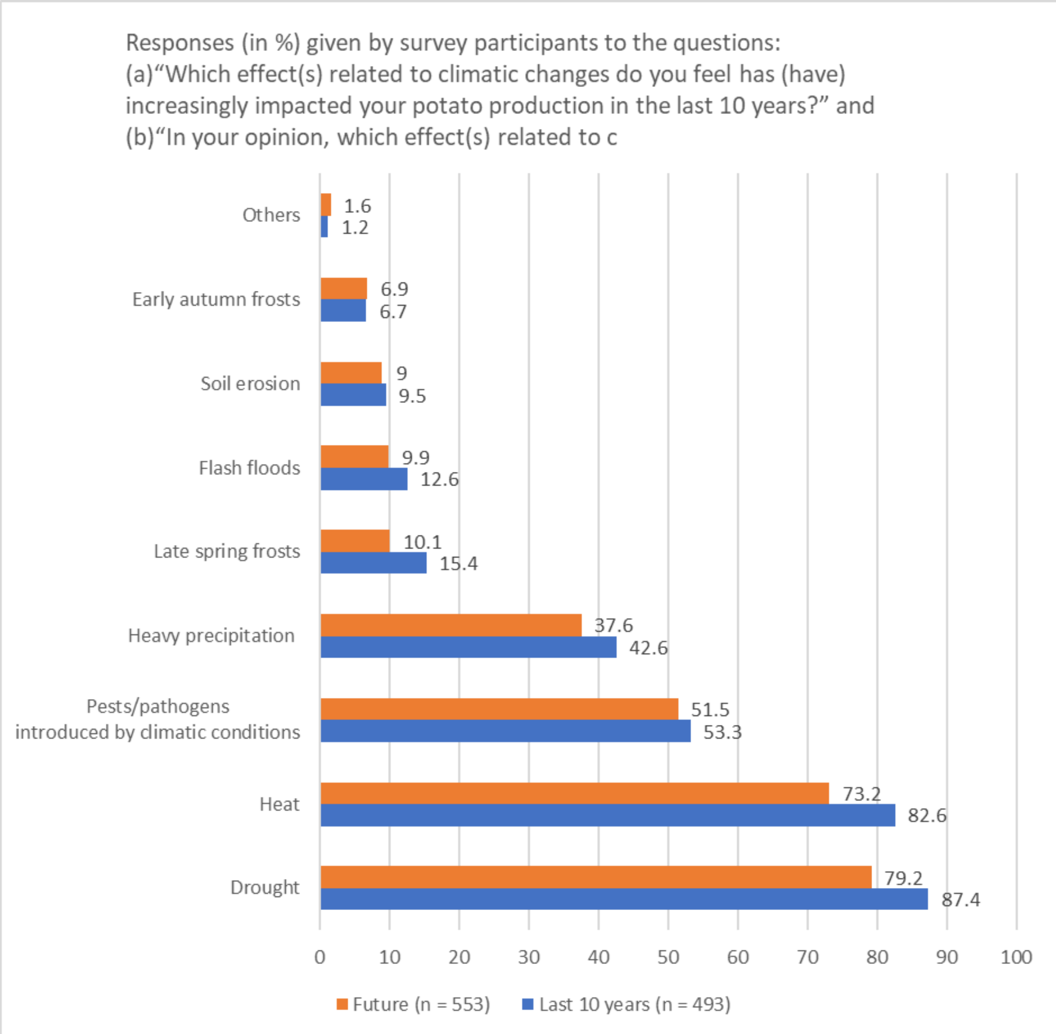
This brief overview demonstrates that potatoes are likely to be impacted by the expected changes to European climatic conditions; changes in precipitation and temperatures will directly impact tuber yield and quality, but also indirectly by altering soil functions and water balances and increasing the risk of pests and diseases. A survey of 553 potato farmers[11] carried out in 2021 by the ADAPT project[12] effectively demonstrates the effect climate change already has on potato production in Europe: 89% of respondents confirmed that changing climatic conditions have impacted them in the last ten years. The **top three threats identified by farmers as impacting on both past and future production are droughts, heat and pests and pathogens**. Heavy rainfall has affected production according to 42.6% of the surveyed farmers but is perceived to be threat in the future by only 37.6% of respondents (see Table 3) (von Gehren et al, 2023).

Higher levels of atmospheric CO_2 concentrations, on the other hand, may positively affect potato production (George et al, 2022). An assessment by Raymundo et al (2018) predict **moderate global yield declines of 2% to 6% by 2055 and larger decreases of 2% to 26% by 2085 (without adaptation).** Modelling results reported by Jennings et al (2020), on the other hand, suggest **yield increases ranging from 9 to 20% globally with adaptation by 2050**, i.e. a changing of planting dates and better adapted cultivars. Similar findings are reported for Europe by the SolACE project (George et al, 2022). The project's modelling exercise showed that, in the north, centre and west of Europe, potato yield increases could be achieved due to favorable changes in precipitation and temperature that allow the crops to benefit from the increased atmospheric CO_2 levels. In contrast, production in the east and south of Europe is predicted to decline as a result of high temperatures and water scarcity. However, the authors highlight that, when different adaptation measures are applied, yield projections change. Against this backdrop, George et al (2022) conclude that in order to

[11] The majority of replies were received from farmers from Austria, the Netherlands, Germany, France, Switzerland, Slovenia, Belgium, Poland, Spain and the United Kingdom.
[12] https://adapt.univie.ac.at/

benefit from the potential positive impacts of increased CO_2 levels, crop production will need to effectively manage and adapt to the biotic and abiotic stresses resulting from climate change.

Table 3. Climate change related difficulties for European potato farmers



(Source: von Gehren et al, 2023)

3.2.3 Cropping practices

The literature identifies a range of strategies that could potentially increase resilience to the direct and indirect climate change hazards threatening potato production. Switching from rainfed to irrigated cultivation, and ideally high efficiency irrigation, is one measure to increase drought resilience that is widely discussed and investigated in the literature on potato cultivation (Reay, 2019). Irrigation development is bound to increase in the coming years as farmers are likely to want to maintain their production rather than transition to alternative crops which comes with new economic burdens. However, irrigation development is contingent on available water sources and farmers would also need to invest in new infrastructure (Lynn, 2022). A survey carried out by van Gehren et al (2023), showed that out of the 553 questioned farmers, only 34.7 were equipped for the possibility of irrigation.

Moreover, **existing studies do not conclusively demonstrate that irrigation will effectively prevent yield losses due to climate change** (see Egerer et al, 2023 for an overview). A recent assessment of the potential of reducing potato yield losses in Northeast Lower Saxony (Germany) shows that, for a high emissions scenario and without irrigation, potato yields will decrease by 18% on average until 2050. Losses were shown to be halved with irrigation at current levels and minimized by up to 80% with irrigation at double the current levels. Whilst the authors acknowledge that yield losses might be further reduced due to higher levels of atmospheric CO^2, they conclude that irrigation only has limited capacity to minimize yield losses. First, the higher irrigation levels, the lower its effectiveness to prevent yield losses as irrigation levels and yield losses rise in parallel. Second, as water becomes a limited resource under climate change conditions, requirements by other sectors will limit the amount available to agriculture (Egerer et al, 2023).

The **adoption of better adapted or improved crop varieties can be another important adaptation strategy for potatoes growers**. Efforts to breed more resilient varieties are ongoing but will require time[13]. Against this background, several cropping practices may increase the climate change resilience of potato cultivation in the short and medium term, by maintaining soil moisture levels, lowering soil temperatures, and reducing the occurrence of pests and diseases. The cropping practices most frequently reported on in the literature in connection with resilient potato production in Europe are mulching and mixed or intercropping.

Mulching

Research suggests that covering soils with organic materials, such as grass, weed cuttings or wheat straw, can help regulate soil temperatures. Depending on the **mulching** material used, its colour, and time and date of application, soil temperature may decrease or increase. During the day, it **can prevent heating of the soil and during night protect it from cooling down too much** (Adamchuk et al, 2016). In addition, by preventing solar radiation from

[13] See e.g., the Horizon 2020 project ADAPT – Accelerated Development of multiple-stress tolerant Potato, https://adapt.univie.ac.at/

penetrating the soil too deeply, mulching is thought to **reduce evaporation, and maintain soil moisture** levels favourable to potato cultivation.

Mulching experiments carried out in potato plots in Western Hungary show that **a mulch layer can regulate soil temperatures; soil temperatures measured in the trials were consistently lower in hay mulched plots than in control plots**. The difference between the average daily soil temperatures in the treated versus the control plots was 1.155°C and the mean daily temperature of treated plots was significantly lower. Results indicated that the mulching was particularly successful in reducing maximum temperatures rather than evenly reducing the average temperature. (Dudas et al, 2016). Adamchuk et al (2016) observed in their mulching trial of potatoes in Ukraine that the straw layer prevented an overheating of the soil surface, particularly during the hot hours of the day. On the mulched plot, the daily temperature of the soil surface varied between 16.5 to 20.5 ºC compared to 16.0-32.0 ºC in the control plot. Temperatures on the control plot therefore exceeded the temperature limits which are considered favourable for potato plants for a substantial amount of the day, with potential adverse effects on tuber formation. These findings correspond with results obtained in experiments with different mulching materials in Europe (Kral et al, 2019). Nerinckx (2021), for instance, shows that soil temperatures in potato plots mulched with straw and flax in filed experiments in Belgium reduced soil temperatures by around 54.5% compared to that measured in ridge cultivations.

Several studies concluded that mulch applications may positively impact soil moisture content of potato fields (Döring et al., 2005; Adamchuk et al, 2016; Kral et al, 2019). For instance, experiments carried out in Austria with grass cuttings as mulch helped maintain soil moisture in one of the test sites during the very dry and hot summers of 2013 and 2015; considerably higher yields than on the un-mulched control plots were recorded. However, on a second plot, no differences in tuber yields could be observed which the authors attribute to the specific soil type (pararendsine with high coarse grain content). In addition, in 2014, a comparatively wet year, no differences in yields were recorded (Hein and Waschl, 2015). These findings illustrate that the local biophysical and climatic conditions determine whether mulching will have positive effects on a potato farming system and thus its ability to adapt to climate change risks (see also Finckh et al, 2015).

Research suggests that a sufficient layer of mulch can inhibit the emergence of weeds. Adamchuk et al (2016), upon observing that the mulched plot of their three-year mulching trial was free of weeds during the entire vegetation period, straw is a reliable way of weed control in potato plantations. Moreover, studies suggest that mulching can be an effective way of reducing diseases caused by pests and pathogens. Experiments conducted by Dvořák et al (2013) showed a significant decrease of the number of Colorado potato beetle larvae (Leptinotarsa decemlineata) in potato plots mulched with grass cuttings.

According to Döring (2004), straw mulch applied on potatoes in two organic experimental sites in Germany significantly reduced the infestation of potato leaves with aphids, the main vector for the Potato virus Y (PVY). The same experiment showed no significant effect on the severity of late blight, but a trend reducing late blight was observed.

According to Döring (2004), straw mulching used to be very common in potato cultivation in North America to maintain soil moisture levels and as a means of pest control. It started to disappear with the more widespread introduction of sprinkler irrigation and herbicides. The author highlights that, with this shift, other positive effects of the practice were also lost, the reduction of soil erosion being the most significant co-benefit. Field trials by Döring (ibid) showed **a reduction in soil erosion by 97 % in a rain simulation experiment** on a 8 % sloping potato field with 20 % crop cover.

A **considerable number of studies report positive effects of mulching on potato yields, with evidence demonstrating an increase or at least equal output levels when compared to non-mulched plots**. Results from 11 field experiments in Germany showed no significant differences in yield and tuber size distribution by the application of straw mulch (Döring, 2004). Dvořák et al (2012) compared the effects of different mulch materials, chopped grass and black textile, on potato yields in two different regions of the Czech Republic. Results showed that yield (on average of sites and years) in plots with chopped grass mulch was 22.9% and on plots with textiles 7.4% higher than in non-mulched plots. This positive effect on yields is confirmed by findings reported for experiments carried out with compost, walnut, mixed leaves, and straw in Hungary (Südiné Fehér et al, 2024), straw in Ukraine (Adamchuk et al, 2016), and the Czech Republic (Kràl et al, 2019; Dvořák et al, 2012), and straw and flax in Belgium (Nerinckx, 2021). The magnitude of these effects reported by the studies, however, varies significantly with increases ranging from 10.1% (Kràl et al, 2019) to 30-40% (Adamchuk et al, 2016). In addition, some studies suggest that the number of tubers and their weight may also increase through mulching (Dvořák et al, 2012; Adamchuk et al, 2016).

Döring (2004) suggests that **varying effects of (straw) mulch on tuber yields can be attributed to differences in climatic conditions, with yields more likely to increase when mulch is applied in hot and dry summers**. This is thought to be due to lower evapotranspiration and soil temperatures of fields covered by mulch. By the same token, if applied in cooler climates or too early, mulch can lead to below-optimum soil temperatures and thus reduced potato yields. Finckh et al (2015) conclude that the effects of mulching (as is the case for other practices) depend on the site-specific biophysical and (variable) climatic conditions (see also Dvořák et al, 2012; Král et al, 2019).

Table 4 summarises the main effects and potential problems of mulching in potato systems, pointing to the main considerations to be taken into account when adopting this practice.

Table 4. Effects and potential problems of mulching on potato systems

Effects	Potential problems
Reduces soil temperatures, particularly early in the growing season.	Retarded early plant growth.
If applied too late may suppress already emerged potato plants.	Early in the season not enough mulch materials may be available.
Increased solar light reflection and therefore dryer canopy.	In extremely hot conditions may get too hot if no canopy closure.
Protection from drought.	Too much water could sometimes become a problem.
Reduced damage to foliage as no more ridging carried out.	If too little mulch is applied or if the mulch disappears too quickly, weed problems may result.
Possibility for fine roots to grow undisturbed into the mulch and to use this as direct source of nutrients.	Insufficient depth of planting and first hilling may result in some green tubers.
Erosion control.	Cooler and moister soils may pose a problem depending on site

(Source: Finckh et al, 2015)

Döring (2004) states that **some of the effects of mulching can be controlled by adapting the application rate to the climate conditions, i.e. thickness of the mulch layer**. Importantly, the author highlights that the positive effects of mulch on soil erosion and virus control are not compromised if lower amounts are applied during wet and cool summers. Moreover, as mulching can be labour-intensive and requires the availability of materials to use (Král et al, 2019, Finckh et al, 201), a lower application will reduce the costs for material and spreading

(Döring 2004). Finckh et al (2015) note that once the mulch is applied, no more mechanical weed control needs to be carried out, saving labour and energy as well as reducing the damage to the potato foliage from mechanical operations which makes the plants more susceptible to infections.

Mixed/Intercropping

As described above, European potato farmers typically grow potatoes in rotations of three or more years with other crops, such as maize, cereals, sugar beet, rape seed and vegetables to replenish soil resources and reduce the build-up of soil borne diseases and weeds (Nerinckx, 2021). As results from the SoLace[14] project show, a strategically chosen 'pre-crop', i.e., the crop preceding potato can improve soil structure, and increase organic matter and fertilization (Darbon, 2022). However, one of the main reasons for growing potatoes in rotation systems is to prevent crop diseases and pest outbreaks. For instance, Möller and Kolbe (2003) explain that by increasing the frequency with which potatoes are grown in a rotation by a third, average yield will decline by 15% in the long term mainly due to nematodes. **Intercropping or mixed cropping are further techniques that are used to suppress pests in potato cultivation around the world**, although only limited evidence from European trials were found.

Two intercropping variations, strip intercropping and under have been investigated for their ability to reduce pest occurrence in Germany (Bouws and Finckh, 2008; Stumm and Köpke, 2008), and the Netherlands (Sondh, 2018). Findings from **field strip cropping** experiments at an organic experimental farm indicate that growing potatoes in narrow strips perpendicular to the wind and separated by non-potatoes **may in general reduce epidemic pressure within this type of farming system** (Bouws and Finckh, 2008). Similar results were reported for intercropping trials conducted by Sondh (2018) where infestations with late blight were significantly lower in the intercropped plots compared to the controls. Stumm and Köpke (2008) where **undersown crops significantly reduced late weed infestation** over the three-year trial period. Their study demonstrated that undersowing was particularly successful in reducing late weed infestation in potato varieties that have low resistance to late blight. These findings confirm earlier results reported by Kainz et al. (1997) and Haas (1999).

The literature indicates that the following factors influence pest reduction effectiveness of intercropping/mixed cropping in potato cultivations:

[14] SolACE - Solutions for improving Agroecosystem and Crop Efficiency for water and nutrient use, https://www.solace-eu.net/index.html

- Choice of the second crop: some crops have been demonstrated to be more effective in suppressing weeds, for example oil radish (Stumm and Köpke, 2008), this benefitting yields. Others offset positive weed suppression effects with increased competition for water and nutrients as was the case in potatoes and wheat intercropping experiments carried out by Bouws and Finckh (2008).

- Size and spatial orientation of strips: Bouws and Finckh (2008) showed that in larger plots of strip-cropped potatoes (6 × 18m and 6 × 36m compared to 3 x 10m), disease was significantly reduced by 9–20% and 4–12%, respectively, compared to pure stands of potato on the smaller plots. The greatest reductions were achieved in plots planted perpendicular to the wind. Similar results are reported for strip-cropping experiments in the Netherlands (Sondh, 2018).

Intercrops (and cover crops) can be harvested or used as 'green manure'. Given a decrease in animal manure in many parts of Europe, transportation costs and restrictions imposed by the EU Nitrates Directive[15], there is an increasing interest in finding alternatives to common fertilizers, but the focus of existing studies has been on "cut-and-carry" practices with green manure (Palomba, 2016). "Cut and carry" means that green manure crops are grown in one field and then harvested and transported to the field(s) where the fertiliser is required rather than using intercrops as an alternative fertiliser directly where they are grown. Several studies carried out in the Netherlands demonstrate that yields are higher or similar when applying green manure, compared to animal manure (Palomba 2016; Litsos, 2015; Drakopoulos, 2014). **Results from the US** (Porter et al, 2016; Halloran et al, 2013) and Canada (Nyiraneza et al, 2021) **show that green manure can increase soil carbon and nitrogen and improve soil structural characteristics such as water retention capacity and the capacity to suppress diseases.** The scarcity of European studies suggests that using intercrops as green manure is not yet widely implemented in potato cultivation here.

On top of reducing pest occurrence, **intercropping or mixed cropping practices are reported to reduce soil erosion.** Undersowing, for instance has shown to reduce soil erosion in the soil after potato harvest (Kainz et al, 1997; Haas, 1999). Gerl & Kainz (1999) estimated that erosion can be reduced by more than half by covering the soil with undersown crops compared to unprotected potato ridges.

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[15] Council Directive 91/676/EEC concerning the protection of waters against pollution caused by nitrates from agricultural sources (Nitrates Directive): The Nitrates Directive aims to prevent and reduce water pollution from agricultural activities. It requires EU Member States to monitor the quality of water and develop action programmes and measures related to using and handling fertilisers and manure. The Directive sets a maximum limit value for nitrate of 50 milligrams per litre. For further information, see https://environment.ec.europa.eu/topics/water/nitrates_en.

Similar findings are reported from other parts of the world, where intercropping is more widely applied in potato cultivation. Nyawade et al (2020) for instance showed that the high canopy of potato-legume intercropping created shade that optimized soil temperatures and increased the soil water content. The dense canopy also intercepted and reduced raindrop-hitting force and slowed down the velocity of runoff, this reducing soil erosion and soil organic matter loss.

In terms of yields and costs, findings reported by Stumm and Köpke (2008) indicate that **undersowing has no negative effects on either the salable yield or the quality of the potatoes**. They conclude that, from a business perspective, undersowing can be a highly profitable praxis since the planting of the second crop can be integrated into other operations such as hilling or weed removal, using existing equipment. In this case, they estimate the costs for the measure to be just €40 for the seeds (mustard or oil radish, at 2008 prices). One limitation highlighted by Stumm and Köpke (2008) was the need for sufficient soil moisture at the time of sowing the second crop. Their results indicate that with very dry conditions, the development of the undersown crops is not sufficient to enable an effective reduction in late weed infestation. This means that fields might need to be irrigated in order for undersowing to effectively reduce pests. The positive effect of intercropping practices on yields was demonstrated by Sondh (2018). The author reports fresh yields in stripcropped potatoes were significantly higher than in monocropped cultivations. If used as green manure, intercrops could reduce fertilisation costs to farmers.

Other practices

There is a **rich literature reporting insights from the use of sustainable practices in potato cultivations from other regions of the world**. For instance, conservation tillage and cover crops are commonly used in the US and Canada in rotation with potatoes and which has shown to improve soil characteristics and suppress soil-borne potato diseases (Larkin et al. 2010; Larkin and Halloran 2015). Larkin et al (2010) report that cover crops can help manage diseases by (i) serving as a break in the host–pathogen cycle; (ii) changing physical, chemical or biological soil properties, resulting in the stimulation of microbial activity and a diversity or an increase in beneficial soil organisms, which also can inhibit pathogens, and (iii) producing substances that supress pathogens and/or parasitic nematodes in potato cultivations.

Few studies report experiences with these practices in potato cultivations in Europe. However, **anecdotal evidence suggests that a small but growing number of farmers – both organic and conventional - are transitioning to regenerative agriculture.** Regenerative agriculture describes an approach that focuses on soil and crop health to increase yield resilience while creating positive impacts on carbon and water cycles and biodiversity. Healthy soils are considered the key prerequisite for productive agriculture, with the three core principles being: (1) no tillage, including direct sowing; (2) permanent ground cover with plants or plant residues and (3) promotion of biological diversity including expanded crop rotation (Kurth et al, 2023). The practices associated with these principles are already widespread in cereal farming systems, but are not yet common practice in potato cultivation, due to the specific nature of potato farming system. Hence, experiences of regenerative agriculture are limited but some practices have proven to be beneficial (see Box 9) (Nimmrichter, 2021).

Box 9. Growing potatoes in Germany using regenerative agriculture practices

Traditional German cuisine, whilst rich and diverse, is often built around two main ingredients: meat and potatoes. Indeed, none of the hearty, and rustic dishes Germans refer to as 'Hausmannskost' could exist without the Germans' 'Lieblingsknolle', or favourite tuber, the humble potato. On average, each German consumes around 56.1kg of potatoes per year, including (BLE 2023).

Germany is the top producer of potatoes in the EU, producing a total of 10.3 million tons of potatoes in 2022 (ibid.). However, due to the extremely dry weather throughout the entire growing season, yields per hectare reached a historical low in 2018 at 353.8 decitons per hectare (dt/ha) and were only lightly higher in 2019 at 390 dt/ha (Nimmrichter 2021). On top of hotter, dryer summers, farmers are faced with an increasing pesticide and fungicide resistance of pathogens and disease carriers. Many soils have a soil organic matter content of less than 1% following years of intensive cultivation – only 4% of potatoes grown in Germany were cultivated using organic farming methods in 2020[16] - negatively impacting on

[16] Klim (2024) Kartoffeln anbauen: Regenerative Methoden für Ertrag und Bodengesundheit, https://farms.klim.eco/article/regenerativer-kartoffelanbau-0ca61c80-df1f-47cf-afe4-62e6d858c6f8, accessed 25.03.2024.

water retention capacity and nutrient supply of plants (Nimmrichter et al, 2020).

Against this background, some farmers are turning to the concept of regenerative agriculture. Three farmers share their experiences with regenerative agriculture (Nimmrichter, 2021):

- A conventional farmer cultivating potatoes on 15ha of his land in Bavaria (southern Germany) uses cover crops, conservation tillage, compost tea[17] and no glyphosate reports higher organic matter content, and a better soil structure overall. The farmer observed that, during heavy rainfall events (80mm of rain in 20 minutes), the dams remain stable.

- A conventional farmer who, for the past three years, has been applying regenerative farming principles to grow potatoes on 35ha of his conventional farm in Lower Saxony (northern Germany) reports a significantly lower level of weed emergence. Fertiliser use could be reduced, and the soil has a very good structure. The farmer uses conservation tillage, a cover crop that is integrated into the soil, undersowing, no glyphosate and transfer mulch.

- A third farmer from neighbouring Austria has been working according to regenerative agriculture principles for the past ten years, using mulch and compost tea to cultivate potatoes organically. The farmer acknowledges that these farming methods are more labour intense that conventional practices but highlights that the additional effort is offset by higher yields and better, healthier tubers; there are no problems with the Colorado Potato Beetle.

[17] "[...} Compost teas [...] are organic liquid products that come from the mixture of mature compost with tap water in 1:5 or 1:10 (v/v) ratios for a specific period of incubation" (Gonzalez-Hernandez et al, 2021, p.2.

Box 10. Key messages

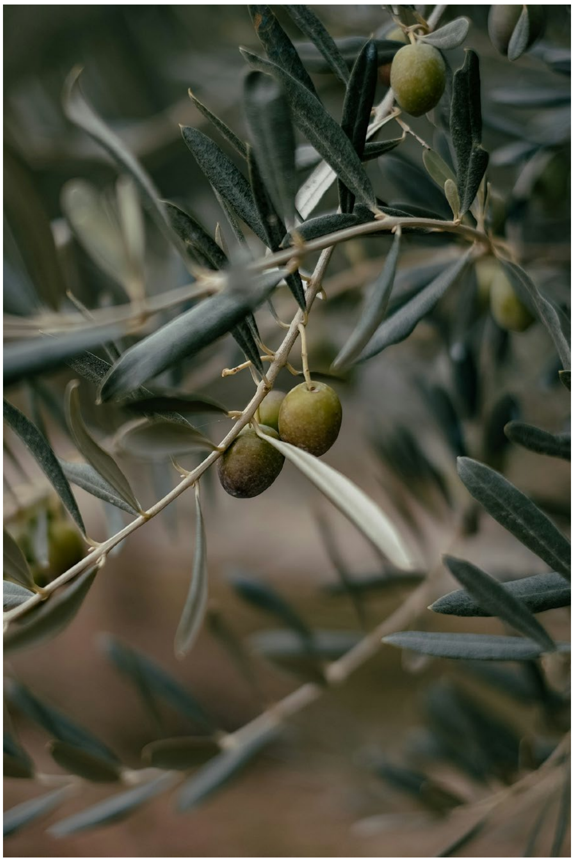
Europeans top the table of potato consumers worldwide, with **each European eating 90kg per year on average**. As a low-fat food, rich in protein, starch, minerals, and vitamins and with a caloric density higher than any other commercial crop, it plays a key role in global food security. The **EU is the second largest producer globally** (37% of total production).

Temperatures above 30°C during growing season can reduce the number and size of potatoes developing. Physical defects such as hollow heart, tuber cracking, and skin russeting are more likely. Potatoes are extremely sensitive to **water deficits** due to a shallow root system, negatively impacting tuber quality and yields and potentially leading to higher glycoalkaloids content, toxic compounds that can cause gastrointestinal and neurological symptoms. Waterlogged soil due to **heavy rainfall** prevents oxygen exchange, leading to diminished root growth, and the decaying of the inner potato tissue. Climate hazards may lead to favourable conditions for some pests and the migration of beneficial organisms from warmer to colder climates and may disrupt the plants' natural defence mechanisms against **pests and pathogenic organisms**. Projections of climate change on **potato yields** vary, ranging from global yield declines of 2% to 6% by 2055 (without adaptation) and increases of 9 to 20% globally (with adaptation) by 2050. It can reasonably be expected that in the north, centre and west of Europe, potato yield increases could be achieved due to favourable changes in precipitation and temperature while production in the east and south of Europe might decline because of high temperatures and water scarcity.

Mulching may lower soil temperatures and help maintain soil water moisture in hot and dry conditions and could increase resilience of potato cultivations to heat and drought. Mixed or **intercropping** has shown to reduce pest occurrence and soil erosion. Positive experiences with other techniques, most notably **conservation tillage and cover cropping** are described for the US and Canada but are not widely reported for Europe. In field trials, mulching has resulted in increased or at least equal output levels when compared to non-mulched plots under hot/water scarce conditions. Higher yields of 10% and up to 30-40% are reported. Mixed/intercropping studies find **no negative effects on either the saleable yield or the quality of the potatoes**.

Local biophysical, and climatic conditions determine if mulching will positively impact on potato production. Some of the potential problems, such as lowering soil temperatures below the optimal level, can be controlled by adapting the thickness of the mulch layer. As mulching can be labour-intensive and requires the availability of materials, tailoring application rates may reduce the costs for material and spreading. Mechanical weed control is no longer needed following application, saving labour and energy. Intercrops, if used as green manure, could reduce fertilisation costs to farmers, and planting of the second crop can potentially be integrated into other operations such as hilling or weed removal, using existing equipment.

3.3 Olives



In 2013, the **UNESCO recognised the Mediterranean Diet as an intangible cultural heritage of humanity**[18]. Whilst the term 'diet' is usually associated with some form of restricted eating its roots in the Greek díaita, suggest it refers to a **"way of living", or "life regime"** (Corominas, 2000). Hence, the Mediterranean Diet does not simply stand for a nutritional regime, it encompasses a range of skills, knowledge, practices, and traditions revolving around agriculture, food production, preparation, and consumption[19]. The term was first coined over 40 years ago to describe the way of living and eating common to the countries around the Mediterranean Basin (see **Box 1**).

Since antiquity, the olive tree has been intrinsically linked to the culture, the nutrition, and the economy of this region (Loumou and Giourga, 2003). And although it is recognised that the Mediterranean Basin encompasses many different cultures and regional cuisines, **olive trees and olive oil are a defining feature of 'Mediterranean ness'** (Meneley, 2020). Olive oil has long been used in Mediterranean cuisine but has increased in popularity in other parts of the world over the last decades. Indeed, global olive oil consumption has almost doubled since the early 1990s[20].

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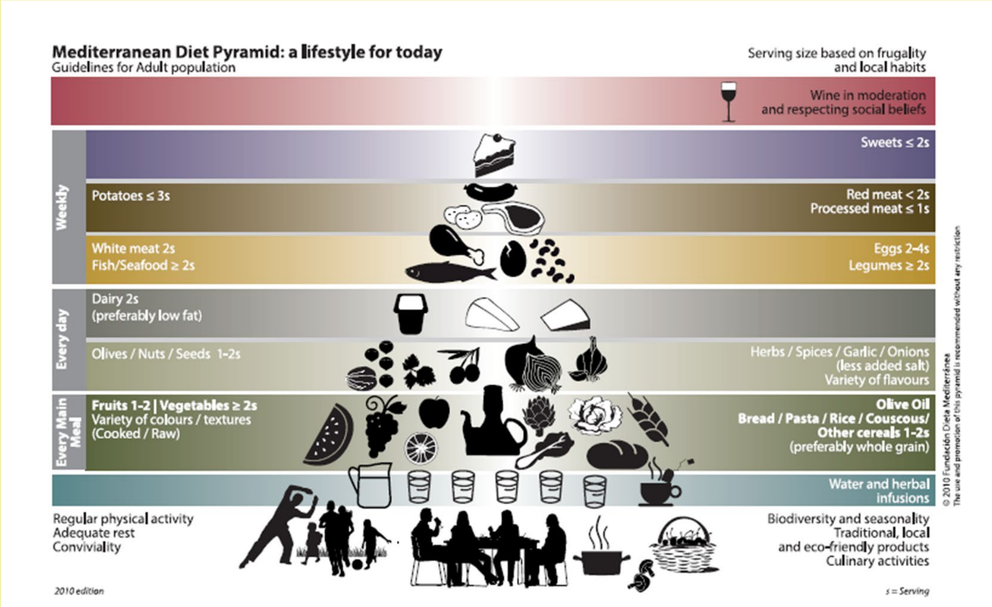
[18] https://ich.unesco.org/en/RL/mediterranean-diet-00884
[19] https://mediterraneandietunesco.org/
[20] https://www.internationaloliveoil.org/changes-in-olive-oil-consumption/?lang=ar

Box 11. The Mediterranean Diet

The Mediterranean diet is rich in plant-based local foods such as cereals, fruits, vegetables, legumes, tree nuts, and seeds, and low to moderate amounts of fish, seafood, and eggs, and low amounts of red meat. Olive oil is the main source of added fat, taking the central place in the Mediterranean Diet food pyramid.



The term Mediterranean Diet was coined by Keys in the 1970s who found that rates of coronary heart disease were much lower in countries Mediterranean countries where olive oil was the main dietary fat compared to northern Europe (Keys, 1970)[21]. Since then, a wealth of studies has demonstrated the profound health benefits of the Mediterranean Diet for lowering the risk of non-communicable diseases, such as cancer, heart disease, obesity, and type 2 diabetes (Willet et al., 2019). It has also been recognized as a sustainable diet because of its lower environmental impact on the use of soil, water and energy and the positive potential for climate mitigation (Castaldi et al, 2022).

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[21] For further information, see https://www.sevencountriesstudy.com/

3.3.1 EU overview

95% of all olive trees in the world are cultivated in the Mediterranean region (Eurostat 2023). Nine EU Member States cultivate olives, Spain, Greece, Italy, France, Croatia, Cyprus, Malta, Portugal, and Slovenia, on a combined total area of five million hectares (Rossi, 2017). According to the 2017 EU orchard survey[22], Spain accounts for 55% and Italy for 23% of the total EU area under olive trees (Eurostat 2019)

In many areas of the Mediterranean the olive tree is the main crop and primary source of income for a large percentage of the rural population (Loumou and Giourga, 2003). According to the International Olive Oil Council (IOC), Olive oil production has tripled in the last 60 years[23]. Indeed, most of the olives grown in the EU are used to produce olive oil and a comparatively smaller share are eaten as table olives: **of the approximately 3 million tonnes of olive oil produced every year worldwide, the EU supplies around 68%** (equalling around 2 million tonnes); in addition, the bloc produces 866 thousand tonnes of table olives per year (European Commission 2020). **Spain is the top producer of olives for olive oil in the EU and the world**. In 2022, Spain accounted for 48.7% of the EU production, followed by Italy (27.5%), Greece (12.5%), and Portugal (10.3%) (Eurostat, 2023). Around **50% of the world production of olive oil is consumed in the EU**, with Greece ranking first in per- capita consumption (12kg per person per year) (European Commission 2022).

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[22] The survey is carried out every five years; updated statistics are due to be reported I 2025.
[23] https://www.internationaloliveoil.org/the-world-of-olive-oil/?lang=fr

3.3.2 Impacts of climate change on olive cultivation

The Mediterranean region is largely characterised by a semiarid climate, with mild, wet winters and hot, dry summers (Michaelides et al, 2018). Water is a scarce resource in the Mediterranean and rainfed crops are frequently exposed to water deficit conditions. The **projected climatic trends are expected to exacerbate the water shortage in the Mediterranean region**: the average temperature is estimated to increase by 0.5 to 2.0°C until the year 2100– if GHG concentrations can be reduced to levels compatible with the long-term goal of the Paris Agreement of keeping global temperature below +2°C above the pre-industrial level - while precipitation is expected to decrease by around 10 to 30% (MedEC, 2020). Records show that, already, **the frequency and intensity of droughts have increased in the Mediterranean region since the 1950s** (MedEC, 2019). This trend is set to continue. For example, in 2023, a severe drought affected the Western Mediterranean following a 12-month period with temperatures up to 2.5°C higher than average, and long and intense heatwaves (Toreti et al, 2023). On top of this, climate change is thought to further contribute to the already widespread soil degradation processes in the region (Ferreira et al, 2022). An abundance of shallow soils (Lagacherie et al., 2018) and typically low levels of soil organic matter (Aguilera et al., 2013) make the region especially susceptible to soil erosion. The **Mediterranean already as the highest soil erosion rates within the EU** (Panagos et al, 2020), a phenomenon set to increase, especially with more frequent intense rainfall events.

Olives are often grown on steep slopes and in relatively poor soils production. Tillage is commonly used by olive farmers to control weeds, making olive cultivation particularly sensitive to soil degradation processes, which reduce the potential yield (De Graaff and Eppink, 1999). Traditional production systems typically grow olives under rainfed conditions, with low tree densities and using few resources (e.g., machinery and human resources) and production factors (e.g., water and fertilizers) (Cabezas Luque, 2022; Silveira et al, 2022). Over the past 30 years, more intensive systems have expanded and to some extent replaced these traditional olive plantations. Intensive production systems are characterised by a higher tree density, semi-mechanised harvesting and, in the case of super-intensive' systems, the use of deficit irrigation, and semi-mechanised harvesting (Cabezas Luque, 2022).

Olive trees are widely considered to be a relatively climate-resilient crop, well suited for the Mediterranean climate (e.g., Silveira et al, 2023). However, the increasing frequency of drier and hotter weather in summer and autumn, and the subsequent lack of rain and drought periods are expected to impact both crop yield and fruit quality (Ben-Ari et al., 2021). The impacts are already visible, both in terms of production levels and market prices (see Box 6). **In 2022, the total harvested production of olives (for olive oil) in the EU** was 7.6 million tonnes, 4.6 million tonnes less than the previous year's production level and **the lowest harvest since 2000**. **In Spain**, the largest EU producer of olives, **adverse weather conditions reduced production by around 50%** to 3.7 million tonnes (Eurostat 2023). An estimated 2.7 million hectares of olive groves are in Spain, more than 20 percent of olive trees anywhere in the world. Within Spain, Andalusia boasts 60 percent of national olive production. However, a recent study concludes that 80% of Andalusia could become unsuitable for some rainfed varieties should global temperatures exceed the pre-industrial average by 2°C by 2050. It is estimated that 6% of Spain's' agricultural turnover, equalling €550 million, has already been lost to climate change impacts (Sanchez 2022).

Box 12. Olive oil - the liquid gold

In recent years, olive oil has become less affordable for many consumers as it is literally turning into 'liquid gold'. Prices have nearly tripled in Spain over the past four years[24]. In 2021, Spanish Extra Virgin Olive Oil peaked at €2.50 per kilogram, and the Italian equivalent at €4.80 per kilogram. In January of 2024, the price of extra virgin olive oil was reportedly €9.20 per kilogram in Spain, and as high as €9.60 per kilogram in Italy. This represents a price increase of 83% in Spain, and of 58.3% in Italy over the last 12 months[25].

Prices are driven up by olive oil shortages. Prolonged droughts and heatwaves have damaged harvests in much of the Mediterranean region in the last two years. Recognising the importance of olive oil in their national food culture, the Spanish government decided to except olive oil from the current 5% VAT to reduce the financial burden on households[25].

The price hike has prompted a drop in consumption in Spain and has generated other unwelcome side effects: according to recent reports, olive oil has become the most frequently stolen product in supermarkets across the country. Nowadays, instead of simply taking a bottle of olive oil from a supermarket shelf, shoppers will have to ask a member of staff to first unlock padlocks with which the bottles are attached to shelves or remove security tacks[24].

[24] Olive oil becomes most wanted item for shoplifters in Spain, The Guardian, 09.03.2024, https://www.theguardian.com/world/2024/mar/09/olive-oil-becomes-most-wanted-item-for-shoplifters-in-spain?CMP=share_btn_url, accessed 22 March 2024.

[25] Certified Origins (2024) Olive oil market report – January 2024, https://www.certifiedorigins.com/marketreport/, accessed 22.03.2024.

The sections below briefly summarise the main climate change risks and their impacts on olive groves. The focus is on the consequences of projected long-term changes, such as temperature increases, changes in precipitation patterns as well as extreme heat and rainfall events. Other extreme weather events such as hail and rainstorms, floods and subsequent landslides can reduce or completely wipe out woody crops (Olesen and Bindi, 2002) but are not considered here.

Higher atmospheric CO_2 concentrations

Studies suggest that an increase in atmospheric CO_2 concentrations could positively affect crop water productivity due to the stimulation of photosynthesis and the subsequent decrease of transpiration rates (Morales et al, 2016). **Higher levels of CO_2 concentrations could therefore contribute to maintaining olive growth and yield** by minimising water loss through transpiration which is especially important in the already water scarce Mediterranean region (Benitez-Cabello et al, 2023). However, it is widely acknowledged that there is still considerable uncertainty as to whether these positive impacts can offset other effects of future climatic conditions (ibid.).

Increase in average temperatures and extreme heat events

Temperature is a key factor for the development of olive trees. **Higher temperatures, especially during winter, are thought to affect olive flowering**. Olive trees need to be exposed to cold temperatures (about 7–9 °C) over an extended period to trigger inflorescence[26] production in springtime. If these temperatures are nor reached or only for short periods of time, flowering failures occur (Gabaldón-Leal et al, 2017; Fraga et al, 2019). With **increasing temperatures and shifting seasons, flowering is likely to advance and could potentially become out of sync with the life cycle of pollinators**. Pollination success and thus fruit development could be reduced as a result. This can result in reduced pollination success and subsequent lower fruit set (Benitez-Cabello et al, 2023). Together with higher evapotranspiration, this will accelerate fruit ripening and force farmers to harvest less mature, smaller fruits (Gabaldón-Leal et al, 2017; Dag et al, 2013).

Reduction in annual precipitation and frequent heavy rainfall events

Annual precipitation below 350 mm/year compromises olive growth, particularly the development of flowers (Fraga et al, 2020; Ayerza and Sibbet, 2001; Rapoport et al., 2012). On top of this, more frequent, heavy rainfalls during

[26] A group or cluster of flowers on a branch or a system of branches (https://www.britannica.com/science/inflorescence).

warm periods, increase the likelihood of pests and diseases, and increase the risk of soil erosion (Benitez-Cabello et al, 2023). A **decrease in precipitation** is thought to potentially alter the rate and amount of nutrients entering the soil which in turn **affects the composition of the soil microbiome**. This could favour the **emergence of non-invasive species** (Pugnaire et al, 2019). Intensive olive farms are expected to be less affected by lower rainfall levels since they rely on irrigation and the use of fertilisers. At the same time, these intensive operations exacerbate the problems as they result in low soil organic matter (SOM) levels, poor microbial activity, and diversity, thus driving soil erosion and desertification (Cabezas Luque, 2022; Benitez-Cabello et al, 2023, Pugnaire et al, 2019).

Pest and diseases

As for wheat and potatoes, **changed climatic conditions may create favourable conditions for the pests and diseases** (Benitez-Cabello et al, 2023). **Farmers may choose to increase the use of pesticides and herbicides** which could worsen the situations as chemical treatments reduce the diversity and abundance of flora and fauna and fauna and thus a disruption and decrease in biological control mechanisms (ibid.) Moreover, the rise in average temperatures during the summer months is thought to lead to a to a delay in the last flight of the olive fly, which might increase the application of treatments close to the harvesting period. Benitez-Cabello et al (2023) report that, indeed, **analyses in recent years have confirmed the presence of traces of chemical products in crops**.

3.3.3 Cropping practices

According to Cabezas Luque (2022) adaptation measures for woody crops such as olives can be classified into two approaches: i) cultivar selection and breeding, and ii) improvement of infrastructures and agricultural management practices. As it is the case with many other crops, cultivars selection and the breeding of new, more resilient cultivars can be effective adaptation measures. For instance, using cultivars with early flowering dates is a viable option to adapt to a shift in seasonal temperatures in the Mediterranean (Gabaldón-Leal et al, 2017). In addition, it is **crucial to preserve the vast genetic pool of over 2000 olive varieties well-adapted to their regions and well-known for their robustness** (Benitez-Cabello et al, 2023). Breeding has traditionally focused on increasing productivity, oil quality and pest resistance but efforts dedicated to the development of more heat and water stress resilient cultivars are growing (Cabezas Luque, 2022)[27].

[27] See e.g., https://gen4olive.eu/

Cover crops

Research conducted over the years has shown that a sustainable management of olive groves can increase their resilience to droughts and reduce yield losses, in particular for those cultivars that do not benefit from irrigation systems. Practices applied to reduce climate change impact mainly consist of maintaining soils covered and reducing tillage.

The use of cover crops in olive orchards can lead to multiple benefits, notably regarding soil quality, as the main benefit is probably the reduction of soil erosion, but cover crops also contribute to the increase of soil organic matter, soil protection, internal nutrients and water absorption. As illustrated above, soil erosion is one of key threats for olive groves, which will be further enhanced by extreme rainfall events due to climate change (Lorite et al. 2019).

Covering soils is important to reduce surface runoff and erosion given that most rainfall takes place in autumn or early spring, at a time in which the biological activity of olive trees is reduced (Gómez et al, 2009b). If a vegetation cover is present, roots of the plants retain the soil while the aerial part reduces the negative impact of raindrops. The SUSTANOLIVE project [28], which gathered data from 240 exploitations in Andalusia that had applied cover cropping for at least 8 years, found that **erosion rates were four times higher in conventional olive groves (>15 Tn/ha annual soil loss) than in those that maintained herbaceous cover crops** together with organic fertilisers and reduced tillage (<5 Tn/ha annual soil loss) (Lietor et al, 2022a). These findings are confirmed by other studies that conclude that the reduction in soil erosion to be an important benefit of using cover crops in olive cultivations (Martinez et al., 2006; Gomez et al., 2009b; Gomez et al., 2011; Torrus Castillo et al 2022).

The importance of reducing soil losses to maintain olive production in general has been highlighted in by Gómez et al. (2009a, 2011). In these experiments, the authors that compared soil losses between years with cover crops and years with bare soils in the same orchards. A **reduction of average losses of 60% reduction per orchard were observed.** Lopez-Vincente (2021), similarly, that in their experiments losses of soil organic matter decreased by 74kg C ha-1 year-1 in cover cropped orchards compared to plantations with bare soil.

The reduction of soil losses is attributed to the physical protection provided by the cover crops. This aspect is also **likely to improve the resilience of olive production to extreme rainfall events** as evidenced by a study conducted by

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[28] www.sustainolive.eu

Marquez Garcia (2024). Their experiment took place in eight olive orchards located in Andalusia, that used cover crops over four growing seasons, with most of cover crops being spontaneous vegetation. The author concluded that the protective green layer of the cover crops reduced the loss of water, soil and soil organic carbon through rainfall events.

To a lesser extent, cover crops can contribute to the reduction of soil losses through a better infiltration, notably when the infiltration is limited by surface sealing, as the effect of cover crops on infiltration is very small if the irrigation rate is controlled by the saturation of the soil profile or by surface layers (Gomez 2017). Moreover, Vicente-Vincente et al. (2016) suggested that in Mediterranean woody crops culture, the use of cover crops favours the transfer of atmospheric carbon to the soil and have an active role in the stabilization of soil organic carbon (SOC), by providing plant-residue-derived organic carbon.

The use of **cover crops can also contribute to the increase of soil quality thanks to its ability to fix nitrogen**. In this regard, experiments carried out by Rodrigues (2013) recorded a peak of net nitrogen mineralization where the cover crops were grown in the previous season, in comparison with a natural vegetation plot. This study however acknowledged that the benefits of cover-cropping regarding nitrogen fixation is not guaranteed, as for instance in the next growing seasons the increase of nitrogen was only occasional. Results reported by the SUSTAINOLIVE project showed **that nutrient retention capacity of soils was 51% higher in those plots with cover crops occupying the entire surface versus those where inter-row strips were applied**. Higher amounts of organic carbon were also sequestered in fully covered soils, i**ncreasing the water retention capacity of the soils** (Lietor et al, 2022b).

To maximize the benefits of using cover crops in olive orchards, it is **important to tailor the strategy to the specific conditions of the orchard**. This involves carefully considering which type of cover crops to use and what percentage of the orchard should be covered, as there are numerous ways to utilize cover crops. Therefore, the optimal approach will depend on various factors related to the olive farming practices. These factors may include whether the production is traditional or intensive, the steepness of the slope, whether the orchard is rainfed or irrigated, and the density and number of trunks of the trees. Therefore, different crops can be used to implement cover cropping strategies including spontaneous vegetation. The use of nitrogen-fixing annual legumes as cover crops can lead to a reduction of nitrogen fertilizer, which might benefit soil quality (Rodrigues 2015). Experiments carried out by Rodrigues (2015) showed that the legume cover crops planted in different olive orchards persisted over four growing season, demonstrating that they might not need to be reseeded every year, significantly reducing the costs for implementing this measure.

Moreover, annual legumes can increase the competition for water, which is of great importance for rainfed olive orchards, that are often located in drought prone areas. In this regard, early maturing cultivars are well suited to be cultivated as cover crops in olive orchards, as they compete less for water with olive trees since the growing cycle goes from autumn to mid spring, which coincides with the resting period of olives (Rodrigues 2015). However, early maturing cultivars tend to produce less biomass and to fix less nitrogen than late maturing ones. Rodrigues (2015) conclude that they seem to be the best suited crops to being grown in in dry farmed olive orchards with low nitrogen demand in drought prone regions. On the other hand, late maturing cultivars could be a better option for olive orchards with a better irrigation condition as they are likely to produce more biomass and fix less nitrogen (Rodrigues 2015).

Box 13. Transitioning to organic production in Jaen[29]

Era de Nava is a 100 ha family owned rainfed olive grove managed by two brothers, Fermín and José. Situated 500 m above sea level and close to the Sierra de Cazorla in the province of Jaen (Andalusia). In 2019, changes in the management of the grove were introduced. Where they had previously applied synthetic fertilisers, herbicides and tillage, they switched to keeping a vegetation cover, integrating organic matter and other residues into soil and halted the use of agrochemicals. Biodiversity

[29] https://www.climatefarmers.org/es/blog/como-fermin-esta-haciendo-la-transicion-de-su-granja-a-la-agricultura-regenerativa-en-espana/

islands providing habitat and corridors for the local fauna were also introduced.

As a result, soil organic matter, very low in the region (often below 0.5%), increased by 1%. Biodiversity also increased and pests were reduced. There were no changes in productivity although they acknowledged that the new management system required additional working hours. The droughts and poor soil quality in the region made it also more challenging but the new practices increased the family´s connection to nature.

New equipment and training were needed, resulting in an investment close to 30.000 EUR. The training was particularly important to them to gain knowledge on the way that the soil work, with some understanding of chemistry and biology. However, they report annual savings in oil and agrochemicals amounting to 12.000 EUR. They sell their olive directly to the consumer and through cooperatives to ensure a fairer return.

Other practices

Beyond the use of cover crops, **multiple sustainable farming practices can provide benefits for soil quality in olive orchards** and therefore for olive production. Mulching can be considered as one of these practices, as its main benefits concern soil quality. For instance, Bombino (2021) noted in their **mulching trial in olive orchards located in the south of Italy that runoff was reduced by 20 to 32% and soil losses by 75 to 80%** in orchards where mulching was applied compared to those that were tilled mechanically. They further observed that mulching significantly improved water infiltration and SOM content.

Bombino (2021) coupled mulching with cover crops in their experiment. Michalopoulos et al (2020) suggest that these two practices are well suited to be implemented together, as using mulch from cover crop can improve soil quality and soil protection. If well-articulated, the use of both practices can show a strong synergy and contribute to increase the resilience of olive production in Mediterranean climate. When applied together, they may present a **viable alternative to conventional tillage**. Conventional tillage contributes to soil erosion. and negatively affects soil structure and biodiversity (Marquez-Garcia, 2024).

In summary, the reviewed evidence suggests that cover crops, combined with other sustainable practices, might decrease soil losses, thus increasing water retention capacities which could in turn improve resilience to water scarcity. The physical barrier created by cover crops, and other practices such as mulching, can further reduce soil losses and help lower soil temperatures. However, sustainable **farming practices can lead to a yield decrease, at least in the short-term**. Palese et al (2014) noted that yield can decrease in young olive trees when cover crops are introduced but will disappear in mature trees. Gucci et al (2012), therefore, suggest delaying the use of cover crops until the third or fourth year after olive grove planting and depending on tree growth. An experiment reported by Gomez (2017) showed that cover crops planted in early spring led to various soil improvements with output levels similar to those of orchards under conventional tillage. In contrast, the use of cover crops in mid/late spring resulted in comparatively lower yields (Gomez, 2005). These observations highlight the need to implement the right practice, at the right time and in the right place.

Michalopoulos et al (2020) analysed the effect of sustainable farming practices on yield in 120 olive orchards located in Greece for 6 years. These sustainable farming practices included no-tillage, sustainable pruning, mulching of pruning residuals and cover crops, which were all implemented in 60 olive orchards, the other 60 keeping the same practices so a comparison could be conducted. This experience showed very encouraging results as **fruit yield increased by 39% in the olive orchards using sustainable practices,** which could result from an increase of stored carbon and mineral nutrients in soil.

Finally, we note that transitioning to different cropping practices comes with different costs. However, the literature suggests that the sustainable practices reviewed here might not incur extra costs. For instance, reduced tillage could reduce the need for fuel lubricants and machinery required for conventional tillage practices (Lovarelli and Bacenetti, 2017). The same applies to fertilisers, as cover crops and mulching may reduce the need for artificial fertilisers. In addition, these strategies can be optimized to limit the cost of olive production, for instance growing persistent cover crops can prevent annual sowing costs or using pruned residuals for mulching strategies.

Box 14. Key messages

95% of all olive trees in the world are cultivated in the Mediterranean region and is the main crop and primary source of income for a large percentage of the rural population. Of the approximately **3 million tonnes of olive oil produced every year worldwide, the EU supplies around 68%;** in addition, the bloc produces 866 thousand tonnes of table olives per year. Around **50% of the world's production of olive oil is consumed in the EU**. Although it is recognised that the Mediterranean Basin encompasses many different cultures and regional cuisines, olive oil is at the core of the **Mediterranean Diet.**

Higher levels of **CO_2 concentrations** could contribute to maintaining olive growth and yield by minimising water loss through transpiration. **Higher temperatures**, especially during winter, and **lower precipitation are thought to affect olive flowering**. With increasing temperatures and shifting seasons**, flowering is likely to advance and could potentially become out of sync with the life cycle of pollinators**. Changed climatic conditions may create **favourable conditions for pests and diseases.** In 2022, the total harvested production of olives (for olive oil) in the EU was 7.6 million tonnes, 4.6 million tonnes less than the previous year's production level and the lowest harvest since 2000.

Cover crops, combined with other sustainable practices, **might decrease soil losses, thus increasing water and nutrient retention capacities**, **improving resilience to water scarcity**. The physical barrier created by cover crops and other practices, such as mulching, can further **reduce soil losses from surface run-off and help lower soil temperatures**. As a viable alternative to conventional tillage, they have the potential to enhance soil structure and biodiversity. Field experiments suggest that cover crops, especially when combined with mulching no-tillage, and sustainable pruning, **may maintain and even improve yields**.

Realising the positive effects of cover crops and other practices on soil and water parameters with may create a buffer against climate change risks whilst maintaining yields is dependent on the **implementation of the appropriate practice, at the right time and in the right place**. Sustainable farming practices can lead to a yield decrease, at least in the short term, if implemented in 'young' plantations. And cover crop selection needs to take int account the location of the olive orchard and the timing of the flowing of the chosen cultivar. In terms of costs, the reviewed practices may lead to reductions in fertiliser and tillage equipment use.

4. CONCLUSIONS AND RECOMMENDATIONS

The European Environment Agency's (2024) states that **Europe is the fastest warming continent on Earth**. The assessment conclusively shows that extreme heat is becoming more and more common, particularly in southern and western Europe. Drought will increasingly affect all European regions in the years to come.

Whilst all economic sectors will be, and already are, impacted by a change in climatic conditions, agriculture is thought to be particularly vulnerable. The European Union (EU) is one of the world's largest producers and exporters of agricultural products. However, the **EU output of staple crops like wheat, potato and olives which are key to many national and regional food fell sharply due to widespread droughts and other adverse weather conditions in recent years**. In the long run, climate change could not only change what and how we farm in some regions in Europe, but also reshape our national cuisines.

Whilst agriculture is particularly vulnerable to climate change, it also has a particularly strong adaptation potential (Yohannes, 2016; EEA 2024). For instance, projections of climate change on potato yields vary, ranging from global yield declines of 2% to 6% by 2055 (without adaptation) and increases of 9 to 20% globally (with adaptation) by 2050. A meta-analysis of more than 1700 published simulations around the world showed that crop-level adaptive measures increase simulated yields by an average 7–15%. Adaptation measures included inter alia changes in cultivars, planting times, irrigation, and crop residue management (Challinor et al., 2014).

Building up the resilience of farming systems requires that short and long-term climate adaptation strategies are implemented at different scales, and drawing on a full range of knowledge, financial, technical, and cropping actions, and practices (Alvar-Beltran et al, 2021; Devot et al, 2023). The wider adoption of different strategies and on-farm practices framed as nature and nature-based solutions (EEA, 2024), agroecology (Altieri et al, 2015), and regenerative farming (Kurth et al, 2023) are seen as a **pathway to more resilient farming systems that reduce the vulnerability of food production to climate change and variability, and other shocks.** Indeed, there is robust evidence in the wider literature on how different practices can positively impact ecosystem functions that increase resilience, such as water retention capacities or the regulation of soil temperatures (e.g. EJP SOIL, 2022; Altieri et al, 2015)

Our review of the evidence shows that, at least for the studied cropping practices and crops, that **sustainable practices have the potential to contribute to the two important societal objectives of maintaining current levels of food**

production and conserving and improving ecosystem functions and features, which is considered key to farm system resilience.

It is essential that steps be taken to support farmers and households engaged in agriculture to cope with both the threat of climate variability as well as the challenges that climate change will pose on future livelihood opportunities. Climate change is not a singular event. **Policy instruments should focus on facilitating a wider uptake of practices that improve those soil quality, water conservation as well as landscape and biodiversity parameters that will potentially enhance the climate change resilience of farming systems**. Member States are required to dedicate 25% of CAP direct payments to eco-schemes, and a minimum of 35% of European Agricultural Fund for Rural Development (EAFRD) funding is ring-fenced for environmental, climate and animal welfare objectives. Countries should use the flexibilities provided under the current CAP to **design interventions that incentivise farmers to take up those practices that have proven to increase resilience to the specific climate risks projected to affect their region**. This type of targeted support is especially needed to help farmers with up-front investment needs to transition to new agricultural methods.

Identifying the most appropriate practices for different environmental and (current and future) climatic conditions warrants further research. A more comprehensive review covering different types of crops and practices, ideally drawing from national research efforts, could provide valuable insights into the benefits of different practices under different regional conditions. Such a review should also cover the economic implications of adopting sustainable practices, as the literature on the costs of transitioning to and then using new practices is still limited.

The evidence demonstrates that the **positive effect of practices on parameters which enhance resilience and yields depends on a wide variety of factors and is context-specific.** Such factors include environmental conditions, soil types, crop and tree species, the time of planting crops, as well as plant density, among others. Inappropriate agronomic management choices can be detrimental to crop yields or result in a failure to deliver environmental benefits. **Farmers may lack knowledge** regarding the suitability of crop combinations (in intercropping), crop-tree combinations (in agroforestry), density of crops and trees, the selection of practices under specific pedoclimatic conditions, the best time of the year to sow or harvest crops, etc. Hence, **Member States need to support farmers to develop tailored plans for improving sustainability and resilience and invest in increasing their advisory capacity.** Knowledge-sharing platforms and workshops may help to facilitate farmer-to-farmer dissemination of know-how on sustainable practices that is relevant to their circumstances.

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