Food and Agriculture
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Technical guide

BUILDING RESPONSIBLE
GLOBAL VALUE CHAINS
**FOR SUSTAINABLE
TROPICAL FRUITS**

Adapting to climate change in the tropical fruit industry:
a technical guide for avocado producers and exporters

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Abbreviations

APEAJAL	Association of Avocado Exporters Producers of Jalisco [Asociación de Productores Exportadores de Aguacate de Jalisco]
APEAM	Association of Producers and Packers Exporters of Avocado of Mexico, A.C. [Asociación de Productores y Empacadores Exportadores de Aguacate de México]
CCA	climate change adaptation
CIAT	International Center for Tropical Agriculture
COP21	Conference of Parties
CSA	Climate-Smart Agriculture
CNRF	National Phytosanitary Reference Center
EPE	expanded polyethylene
EWS	early warning systems
FAO	Food and Agriculture Organization of the United Nations
FPIC	free, prior and informed consent
GHG	greenhouse gas
HAB	Hass Avocado Board
INECC	National Institute of Ecology and Climate Change
IPCC	Intergovernmental Panel on Climate Change
IPM	integrated pest management
M&E	monitoring and evaluation
NAPs	National Adaptation Plans
NAP-Ag	Integrating Agriculture in National Adaptation Plans
NDCs	nationally determined contributions
SFM	sustainable forest management
TFNet	International Tropical Fruits Network
UNFCCC	United Nations Framework Convention on Climate Change

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Executive summary

Climate change induced by humans has become an observed reality, with countries around the world experiencing widespread and pervasive impacts on ecosystems, people and infrastructure as a result of increases in the frequency and intensity of extreme weather events. The agriculture sector is among the most affected by climate change, absorbing a large share of the total losses and damages caused by climate-related disasters in developing countries. Climate change is impacting global agrifood systems, making the goal of feeding the world's growing population more difficult than ever before. The tropical fruit sector is particularly at risk from the negative impacts of climate change driven by rising temperatures, extreme weather events including tropical cyclones, and associated challenges such as water stress and increased pests and diseases. This poses significant risks for the long-term sustainability of production and trade of important tropical fruits, including avocados.

Climate change adaptation can be described as the process of adjusting to actual or expected changes in climate and its effects. Actions taken now can reduce exposure and vulnerability to climate change impacts and build resilience in agricultural systems to ensure that these systems not only bounce back after climate shocks, but also transform to be better prepared to deal with future shocks and stresses. Some adaptation strategies also contribute to mitigating climate change, by cutting greenhouse gas (GHG) emissions and/or capturing and storing carbon from the atmosphere.

Climate plays a major role in deciding perennial fruit crop's distribution, phenology, fruit quality, and pest and disease incidents. Physiological and yield attributes of fruits are sensitive to changing climate. Environmental factors such as temperature, drought, salinity, flooding, carbon dioxide concentration and pathogens, have the greatest effect on fruit production, as these factors have a direct correlation with the regulatory physiological stages of fruit plants. The impact of climate change on perennial fruit crops is also likely to be more detrimental when compared to annual field crops, as the adaptation capacity of shorter duration crops is generally greater than perennials.

From a trade perspective, tropical fruits continue to be among the fastest growing agricultural commodities. Tropical fruits constitute an important source of economic growth, income, food security and nutrition for the rural sectors of many developing countries. High income growth in developing countries and increased awareness of the nutritional benefits of tropical fruits in developed countries are contributing to the fast growing consumption and global demand for tropical fruits. Globally, pineapple, avocado and mango continue to be the three most significantly traded tropical fruits in terms of export quantities, after bananas. As the industry grows, already stressed natural resources will face additional pressure from climate change and plant diseases that spread faster, which threaten to reduce productivity. Adverse weather events and climate change continue to be major obstacles to production, particularly as the cultivation of tropical fruits takes place in climatically vulnerable tropical zones, where more extreme weather phenomena are expected. Recognizing these challenges, the Responsible Fruits Project has developed this technical guide on climate change adaptation for the avocado export industry. The project builds on more than a decade of FAO's experience working with the private sector on tropical fruits.[1] It works with businesses, farmers' organizations and cooperatives, importers and exporters (henceforth collectively referred to as "companies") and other actors in the avocado value chain, with the aim to improve business performance by helping the industry be more resilient to shocks and more sustainable by strengthening or establishing risk-based due diligence systems. It also provides a confidential environment for peer learning on pre-competitive issues through webinars and other knowledge sharing and capacity development events.

This guide is part of a series of demand-driven products developed by the project. The topic of climate change adaptation was selected in partnership with project participants as a necessary topic to address in the context of buildingresilient and sustainable businesses.

The guide is also aligned with the FAO Strategy on Climate Change, which focuses on enhancing capacities to implement nationally determined contributions under the Paris Agreement[2] supporting countries to adapt to and mitigate the effects and causes of climate change. This is achieved through research-based programmes and projects geared towards adapting smallholder production and making the livelihoods of rural populations more resilient.

The purpose of this technical guide is to:

- provide up-to-date information on recent and projected climate change effects and trends in key avocado producing and exporting countries;
- identify climate change risks and impacts on the production and trade of avocado;
- identify adaptation practices and recommendations that may help to address these risks, minimize negative impacts and build resilience;
- share good practices adopted by companies to address specific climate-related production risks in a sustainable manner; and
- identify gaps in information, research and technical solutions needed to strengthen the availability and adoption of adaptation practices.

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1 This includes facilitating the World Banana Forum, the banana sector's premier multistakeholder platform, and work with over 30 leading agrifood enterprises and industry associations to apply the risk-based due diligence recommendations of the OECD-FAO Guidance for Responsible Agricultural Supply Chains.

2 The Paris Agreement requires each party to outline and communicate their post 2020 climate actions to reduce greenhouse gas emissions and adapt to the impacts of climate change through nationally determined contributions (NDCs).

The guide is for producers and other value chain actors of avocado who are interested in learning more about climate change in the context of their own business systems. It was developed through a consultative process with avocado companies and producer organizations participating in the Responsible Fruits Project. Given the available timeframe to develop the guide and the global nature of the project, there are some limitations to the guide, which were discussed and agreed upon with companies and producer associations participating in a dedicated working group. These limitations include the inability to conduct the field-based, longitudinal scientific research that may be needed to answer specific questions related to climate change impacts over time on avocado under various production conditions. On this basis, **the guide is intended to serve as a means to highlight the climate related risks and challenges producers in certain countries are facing, and the adaptation solutions that they are trialling to reduce these risks,** rather than a comprehensive scientific guide with prescriptive adaptation solutions to fit all contexts.

In terms of the structure of the guide, **Chapter 1** introduces the background and discusses the impact of climate change on global agriculture and tropical fruit production. It also explains the purpose and limitations of the guide as described earlier.

Chapter 2 explains the scope of the guide, including: The countries selected for further investigation into the impacts of climate change on avocado production; the climate trends affecting these countries; and a brief overview of some of the countries' experiences to date in developing National Adaptation Plans for the agriculture sector.

Given the global focus of the Responsible Fruits Project on sustainable **production and trade** of avocado, the selection of countries for further investigation was been informed by their relative importance in **global production and exports**, and as such, constitute important sources of employment and export revenues in the identified countries. On this basis, six avocado producing and exporting countries were selected: **Mexico, Peru, Chile, Colombia, Kenya and South Africa**.

A review of baseline climate trends and future projections for temperature and precipitation for the six countries selected was conducted based on data obtained from the World Bank Climate Risk Country profiles and general country-level data available on the World Bank Climate Change Knowledge Portal.

The World Bank estimates that **average temperatures in all of the major avocado producing countries included in this guide will increase** across all of the five emissions scenarios modelled under climate change.[3]

Precipitation variability (distribution, frequency and quantity during the year) and long-term changes have differentiated effects on avocado production, depending on whether water deficit or water excess is experienced at specific stages of the plant development. Unlike temperature, future precipitation patterns do not show a clear trend and vary depending on the region and producing country. However, **it is expected that wet regions will become wetter, while dry regions will become drier**.

In line with the above discussion on national level climate trends, it is important to understand how countries are planning and coordinating their efforts to address climate change through actions to reduce greenhouse gas emissions and implement adaptation plans at a national level. At an international level, the foundation for these actions stems from the **Paris Agreement**. Implementation of the Paris Agreement by each signatory is achieved through national climate action plans known as **nationally determined contributions** (NDCs), which outline the efforts to be made by each country post-2020 to reduce national GHG emissions and adapt to the impacts of climate change.

Climate change adaptation in the agriculture sectors is among the foremost priorities identified in developing countries' National Adaptation Plans (NAPs). To address the abovementioned challenges, since 2015, FAO and the United Nations Development Programme have partnered to work with countries to integrate adaptation solutions specifically for the agriculture sector (NAP-Ag programme) as part of the broader NAPs. Two of the key avocado producing countries, Colombia and Kenya, are included in the programme. While the plans developed do not focus on the tropical fruit sector, they warrant further consideration given that the identification of climate risk factors for agriculture and the adaptation measures proposed are also relevant for tropical fruit production (e.g. water management, soil conservation, protection of biodiversity, agroforestry, early warning systems, etc.). In the context of the tropical fruit industry, understanding how specific commodity sectors like avocado production and export can contribute towards the achievement of adaptation and mitigation targets set out in the NDCs and NAPs is useful. It may help the industry to align their efforts with those at a national and sub-regional level where they exist and demonstrate to policy makers that collective efforts are being made by industry to support these plans.

[3] The World Bank estimated future mean temperatures until 2100 by using five possible future scenarios that consider the levels of emissions and the Shared Socioeconomic Pathways (SSPs) model. Each scenario analysed countries' emissions, mitigation efforts and development, using average temperatures between 1995 and 2014 as the reference period. The models are SSP1-1.9: Most optimistic scenario, describing a world where global CO_2 emissions are cut to net zero by 2050. SSP1-2.6: Net-zero is reached after 2050 and temperatures stabilize around 1.8 °C higher by 2100. SSP2-4.5: CO_2 emissions start to decrease after 2050 and do not reach net-zero by 2100. Progress toward sustainability is slow, with uneven development and income growth and temperatures rise 2.7 °C by 2100. SSP3-7.0: CO_2 emissions roughly double from current levels by 2100 and temperatures rise by 3.6 °C by 2100. SSP5-8.5: Current CO_2 emissions levels almost double by 2050. The global economy grows quickly relying on fossil fuels and leading energy-intensive lifestyles; the average global temperature is 4.4 °C higher.

In **Chapter 3**, the focus is shifted from national level climate trends to zoom in on the specific climate risks facing avocado production across a range of countries and discusses the impact of these risks on production. Thirteen important climate risks were identified through a review of the scientific literature and consultations with producers and associations from the avocado industry. These risks are categorized according to temperature risks (i.e. increasing temperatures, extreme heat, frost and hailstorms); precipitation risks (i.e. intense rainfall, changes in rainfall patterns, water shortages and drought); and mixed or "other" risks linked to climate change effects including alternate bearing cycle, reduction of pollinators, spread of pests and diseases, soil erosion and strong winds. For each of the risk factors identified, a description is given of the effects on avocado production and impacts on social or economic dimensions of production as well as highlighting some of the specific risks experienced in different avocado producing countries. Understanding these risks can help avocado producers plan to manage them.

Chapter 4 presents the climate change adaptation strategies identified in response to the risks discussed in **Chapter 3** for avocado production. These practices were identified through consultations with key stakeholders from the industry and in the scientific literature. The practices recommended are closely linked to different approaches that promote both climate adaptation and sustainability across multiple dimensions. These approaches include Climate-Smart Agriculture (CSA), agroecology, regenerative agriculture and precision agriculture. A total of 15 adaptation practices were identified as follows: agroforestry, anti-frost systems, drainage systems, early warning systems, integrated pest management, integrated water management, mulching and cover crops, organic fertilizers, plant breeding, protection of pollinators and beekeeping, shade nets, sustainable forest management, waste management, water-efficient irrigation systems, and wind breaks or living fences. The selected practices can help avocado producers adapt to the main climate risks identified, with direct contributions to building resilience to future shocks. A brief description of each practice is given along with the potential for co-benefits on environmental, economic or social dimensions. Examples are also given of adaptation practices in action by companies and producer associations.

Finally, **Chapter 5** summarizes the main findings from the guide and discusses some of the challenges in designing and implementing adaptation recommendations. Gaps in information, research, technical solutions and capacity are discussed and recommendations put forward on how these could be addressed to strengthen the availability and adoption of adaptation practices.

Key messages highlighted in the chapter include:

- **Adaptation to climate change is required to ensure the continuity of global avocado production and trade.** Adapting to climate change will enable companies and producer associations to protect their production systems and care for their environment and workers, while minimizing the creation of new risks associated with increasing GHG emissions and global warming. As such, adaptation will increase the sector's resilience to climate-related shocks.
- **It is clear that extreme weather events will increase in frequency and intensity.** Moreover, it is expected that **multiple climate risk factors will occur concurrently** in the same regions,

which in combination with other non-climatic factors, such as economic slowdowns or pandemics, will increase overall risk to agricultural production systems. Avocado producers need to be prepared to **deal with multiple risks in a synchronized manner**, which can be achieved by combining adaptation practices.

- **Knowledge and information on how to adapt to climate change in the avocado sector already exist**, and many companies and producer associations are taking a proactive role in designing strategies and testing practices in the field to deal with climate change and extreme weather events.
- The selected **adaptation practices highlighted in the guide address multiple climate risks and associated impacts simultaneously**. This is important, as discrete adaptation strategies that deal with only one risk factor at a time will not achieve the desired impact.
- **Climate adaptation is a continuous process that takes time and requires information and data.**
- **Adaptation and mitigation efforts to reduce greenhouse gas emissions should go hand-in-hand** whenever possible. Adopting adaptation practices that have climate mitigation potential will help to not only slow down emissions but may also extend the shelf-life of available adaptation practices. Likewise, mitigation strategies can be designed in a way to contribute to and reinforce adaptation. Some of the adaptation practices identified for avocado production, such as sustainable soil management, agroforestry, sustainable forest management, and waste reduction and management, also have positive effects on reducing greenhouse gas emissions in the production sector.
- **All adaptation practices should aim to contribute to the three dimensions of sustainability.** While the environmental dimension is the clear entry point to promote adaptation in the tropical fruit sector, addressing social (e.g. health of workers) and economic risks (e.g. increased costs to maintain infrastructure) associated with climate change impacts is also crucial to the long-term sustainability of business operations.
- **Further research is needed on climate risks to human health.** Some avocado producing companies have already noted these risks, especially those related to **heat stress and associated illnesses** derived from increasing temperatures and exposure to solar radiation.
- **Women and youth are among the highest risk groups when it comes to climate change impacts, yet limited information is available** on specific risk factors and adaptation solutions tailored to meet their needs. No research could be found on specific impacts of climate change on women and youth vis-à-vis engagement in global avocado value chains. This indicates a clear gap in knowledge for the industry, given the important role women play in harvesting and packing. Gender-disaggregated research is urgently required to better understand the key factors that account for the differences between women's and men's vulnerability to climate change risks, and how to build tailored adaptation strategies to address them.

- Climate change has **implications for food security and nutrition**. Avocados form part of a healthy diet and represent an important source of vitamins and nutrients for consumers in both the producing and importing countries. On this basis, avocado companies could consider how they may support vulnerable populations in their local communities through targeted social outreach programmes that aim to improve food security and nutrition such as public procurement (e.g. school feeding programmes, community canteen services) and food banks.

- **Changes in weather patterns impact livelihoods and revenues of industry actors.** Both production and trade may be affected as production becomes more erratic under climate change conditions and quality is affected by heavy storms, sudden droughts, more frequent pathogens and other changes. Inconsistency of supply of export-quality product can challenge the revenues generated by the sector which has flow-on effects in the upstream segments of the value chain. Unreliable production can also affect the livelihood options for producers and communities and create associated challenges for sustaining healthy and nutritious diets.

- **Enhancing the adaptive capacity and climate resilience of avocado value chains cannot be achieved through a single-actor approach.** The complex challenges associated with climate change impacts are best solved through the cooperation of stakeholder groups including governments, companies, producer organizations, research and training institutes, worker unions, and other civil society organizations. Establishing mechanisms for multistakeholder collaboration would be the most effective approach to tackle the impacts of global warming on the avocado industry in the future.

- **At an institutional and policy level**, FAO's work to support countries to **integrate adaptation solutions specifically for the agriculture sector as part of the broader National Adaptation Plans is an essential step**. An understanding of these plans by avocado producers and exporters would help the industry actors to align their strategies with those at the national and sub-regional level and demonstrate to policy makers that collective efforts are being made by industry in support of these plans. Efforts to generate evidence of the impacts of implementing adaptation practices through better monitoring and evaluation are also needed to further advance these claims.

In terms of outreach beyond the guide, the Responsible Fruits project is committed to supporting avocado producers and exporters globally to deal with climate change and other identified sustainability risks through the generation of practical tools. The project is developing various technical materials and tools tailored to the avocado industry, with some also applicable to the wider tropical fruit sector. These products are discussed in **Chapter 5**. Two tools complement the technical guide on climate change adaptation:

- The gap analysis guide helps companies to compare the sustainability standards and policies they use with the OECD-FAO Guidance for Responsible Agricultural Supply Chains, which is the global benchmark for due diligence and responsible business conduct in the agriculture sector.

- The project is developing a **carbon and water footprint measurement tool** for the pineapple industry. The tool aims to support producers, companies and associations to better understand how they can reduce their carbon emissions and prevent the degradation of water resources through their operations, whether small, medium or large. A similar tool could be developed for the avocado industry if there is sufficient demand and resources are available.

In conclusion, this guide was produced by the Responsible Fruits Project for producers and exporters of avocado who are interested in learning more about climate change and how to adapt to it in the context of their own business systems. It is hoped that the guide will be the starting point for discussion on national, regional and localized climate change impacts on avocado production and stimulate joint planning for research on adaptation solutions to support the long-term sustainability of the export industry. Indeed, more longitudinal research that is commodity and location-specific is needed to better understand climate risks and long-term effects on tropical fruit crops to identify innovative adaptation solutions.

Annex 1 provides a list of additional resources (project websites, publications, etc.) for those who are interested in learning more about climate change and its impacts on agriculture, tropical fruit and adaptation options.

Chapter 1.

Introduction to the guide

1.1 Global significance of climate change and its impact on agriculture: Why is adaptation needed?

Climate change induced by humans has become an observed reality, with countries around the world experiencing widespread and pervasive impacts on ecosystems, people and infrastructure as a result of increases in the frequency and intensity of climate and extreme weather events. These events include hot extremes on land and in the ocean, heavy precipitation, drought, fires and tropical cyclones that are expected to affect all regions of the world now and in coming decades (IPCC, 2021, 2022). The agriculture sectors are among the most affected by climate change, absorbing a large share of the total losses and damages caused by climate hazards in developing countries (FAO, 2018a). Global warming is impacting global food production systems, making the challenge of feeding the world's growing population more difficult than ever before. Although global agricultural productivity has increased, climate change has slowed this growth over the past 50 years (IPCC, 2022). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity and reduced water security, with the largest impacts observed in many locations in Africa, Asia, Central and South America, Small Island Developing States and the Arctic (IPCC, 2022).

In addition, the link between climate change impacts and biodiversity loss is clear. Loss of species, and degradation and damage to ecosystems have been observed in every region due to past global warming (IPCC, 2021, 2022; FAO, 2016). Destruction of natural habitats, deforestation and exposure to synthetic chemicals have all contributed to the loss of beneficial organisms such as pollinators and pest-control regulators, affecting crop production (FAO, 2021b). These risks will continue to escalate with each increment of global warming and have a significant impact on the availability of nutritious food (IPCC, 2022; FAO, 2021b). Loss of genetic diversity also reduces the availability of genetic variation to breed crops to withstand climate change and the biotic stresses stimulated by it and reduces the range of crops and livestock available to provide a healthy diet (FAO, 2021b).

From a global perspective, a summary of observed impacts of climate change on agriculture include (IPCC, 2022):

- overall negative impacts on agricultural productivity with regional differences;
- drought-related crop loss has increased in recent years and has affected about 75 percent of the global harvested area;
- reduced food and water security, especially for vulnerable groups;
- increases in frequency and intensity of droughts, floods and heatwaves;
- diminished water availability;
- increased pressure from pests and diseases;
- loss of biodiversity and ecosystem services (including pollination); and
- future risks will continue to increase in near, mid and long term (2100).

From a social perspective, the impacts of climate change on agriculture disproportionately affect vulnerable rural communities who rely heavily on agriculture for their livelihoods. Women and youth are among the most affected due to their limited access to resources and services; reduced voice in decision-making regarding natural resource management and environmental services; lower endowments and entitlements to land; and limited mobility options to pursue livelihood opportunities elsewhere (FAO 2016, 2018a, 2019b, 2022c). This negatively impacts the daily lives of families by increasing the risk of poverty, food insecurity and malnutrition particularly for women and girls (FAO, 2022b). Action is urgently needed to redress the power balance by proactively targeting the inclusion of vulnerable persons in the development of national climate change adaptation plans to reflect their wants and needs. At the same time, investment is also needed to build the capacity of these populations to adapt to climate related shocks (FAO, 2018a, 2019b, 2021b). The tropical fruit sector is particularly at risk of the negative impacts of climate change driven by rising temperatures, extreme weather events including tropical cyclones, and associated challenges such as water stress and increased pests and diseases. This poses significant risks for the long-term sustainability of production and trade of important tropical fruits including avocados.

Climate change adaptation can be described as the process of adjusting to actual or expected changes in climate and its effects. An urgent call to action was made in the latest Intergovernmental Panel on Climate Change (IPCC) report (2022), which found progress on adaptation uneven across countries, with increasing gaps between action taken and what is needed to deal with the growing climate risk, particularly in lower income countries. Actions taken now can reduce exposure and vulnerability to climate change impacts and build resilience in agricultural systems to ensure that these systems not only bounce back after climate shocks, but also transform to be better prepared to deal with future shocks and stresses.

The agriculture sector also plays a crucial role in climate change mitigation. While it is estimated that agri-food systems contributed to 31 percent of greenhouse gas (GHG) emissions in 2020, the sector also holds some of the most important solutions to meet local and global climate goals (FAO, 2022f). Actions to restore and protect forests and other ecosystems, preserve soils and water resources, minimize agrochemical use, reduce food losses, among others, can promote adaptation, while reducing GHG emissions and storing carbon (FAO, 2016).

1.2 Climate change and its impact on global tropical fruit production and trade

Climate plays a major role in determining perennial fruit crop distribution, phenology, fruit quality, pest and disease incidents (Bhattacharjee *et al*., 2022). Physiological and yield attributes of fruits are sensitive to changing global climate and reproductive stages of fruit trees are the most susceptible to climate change, with implications on the quantity and quality of fruits produced. Environmental factors, such as temperature, drought, salinity, flooding, rise in carbon dioxide concentration and outbreaks of insect pests, have the greatest effect on fruit production, as these factors have a direct correlation with the regulatory physiological stages of fruit trees (Nath *et al*., 2019; Sthapit, Ramanatha and Sthapit, 2012). Although perennial fruit trees have a number of survival mechanisms that allow them to cope with environmental stresses, these come at considerable energy cost, potentially reducing fruit productivity.

The impact of climate change on perennial crops is also likely to be more detrimental when compared to annual field crops, as the adaptation capacity of shorter duration crops is generally greater than that of perennials (Chawla *et al*., 2021). In comparison to annuals, developing a new fruit tree variety may take 15 to 20 years, making it more difficult to compete with the challenges brought about by climate change (Bhattacharjee *et al*., 2022). Some of the common effects of climate change on the phenology of fruit crops are highlighted in Table 1. It should be noted however, that the impacts of climate change are highly dependent on both the fruit crop analysed and the agroclimatic conditions in a particular location. For example, a crop like banana might become less suitable under increased temperature and changed rainfall conditions, but others such as coconut and mangoes might become more productive (Mitra, 2016). For this reason, more longitudinal research that is commodity and location specific is needed to better understand climate risks and effects on tropical fruit crops, adaptation options and opportunities for production in new locations (Sthapit, Ramanatha and Sthapit, 2012).

Table 1. Impacts of climate change on the phenology of fruit crops

Climate change effects	Impacts on fruit crops
High temperature & increased solar radiation	• Increased evapotranspiration and irrigation requirements; potential for increased soil salinity; • affects flowering: early or delayed flowering, poor fruit set, reproductive buds transform into vegetative buds, changes in the timing of fruit maturity; • disruption of pollinator populations and pollination activity; • sunburn damage to fruit and branches, and fruit cracking; • increase in soil temperature can accelerate decomposition of soil organic material, resulting in depletion of soil fertility; • production shift to new areas/changing industry location; and • incidence of new pests and diseases.
Lower precipitation	• Stress prior to or during the flowering and post-blooming periods in perennial fruit plants has a negative impact on yields through lower numbers of fruits and cell reduction of remaining fruit; • fruit and flower drop; and • supplementary irrigation requirements in rainfed agriculture.
Increased precipitation and humidity	• Excessive vegetative growth and flower drop, • waterlogged soils kill off beneficial soil microorganisms increasing disease risk from fungal pathogens (e.g. *Phytophthora* cinnamomi) and reducing water and nutrient uptake; • increase in pests and diseases with faster reproductive cycles; • new pests/minor pests becoming major pests; • increased risks of soil erosion by water runoff in production areas; • plant and fruit losses; and • risk of nutrient runoff pollution of water bodies.
Lower temperature & lower solar radiation	• Can affect flowering, reducing pollination, fruit set, fruit retention and size; and • frosts affect flower buds and flowers, reducing fruit size.
Other extreme climatic events (cyclones, hailstorms, etc.)	• Fruit and flower loss; • tree/plant damage; and • infrastructure damage.
Increased CO_2	• Positive effects of rising CO_2 in plants include reduced stomatal transpiration and increased water use efficiency, higher photosynthetic rates and augmented light use efficiency, leading to greater potential for fruit set and fruit retention. • Rise in temperature and a shift in rainfall pattern may cancel out the positive effects and increasing requirements for water and nutrients (nitrogen fertilizer) may be needed under increased CO_2 growing conditions.

Source: Authors' own elaboration with content adapted from Bhattacharjee *et al*. (2022); Chawla *et al*. (2021); Nath *et al*. (2019); Mitra (2018); Fischer *et al*. (2016) and Sthapit, Ramanatha and Sthapit (2012).

From a trade perspective, tropical fruits continue to be among the fastest growing agricultural commodities. These fruits constitute an important source of economic growth, income, food security and nutrition for the rural sectors of many developing countries. Their importance in global food supply has increased significantly in recent decades. This has been confirmed by the fast expansion in global trade flows, which reached a total of 20.5 million tonnes for bananas in 2021, and 8.4 million tonnes for the four major tropical fruits – mango, pineapple, avocado and papaya – combined (UN Comtrade, 2023). World trade in major tropical fruits expanded by 6.8 percent in 2021, reaching a record volume of USD 10.4 billion in 2014–2016 constant terms (FAO, 2022d). High income growth in developing countries and increased awareness of the nutritional benefits of tropical fruits in developed countries, are contributing to fast growing consumption and positive global demand for bananas and tropical fruits (Altendorf, 2019 in FAO, 2019).

As the industry grows in value, already stressed natural resources will face additional pressure from climate change and faster spreading plant diseases, which threaten to reduce productivity (Liu, 2017). Adverse weather events are major obstacles to production, particularly since the cultivation of tropical fruits takes place in climatically vulnerable tropical zones where more extreme weather phenomena are expected (IPCC, 2022). The effects of global warming are resulting in a higher occurrence of droughts, floods, hurricanes and other natural hazards, which increase the risk of producing tropical fruits. From a commercial perspective, this makes it more difficult to predict marketable surplus year-on-year, and more costly given the perishable nature of tropical fruits, the inputs required and infrastructure needed to supply international markets. This challenge cuts across the export industry since the majority of tropical fruits are produced in remote, informal settings, where cultivation is highly dependent on rainfall, prone to the adverse effects of increasingly erratic weather events and in many cases disconnected from major transport routes (FAO, 2022e).

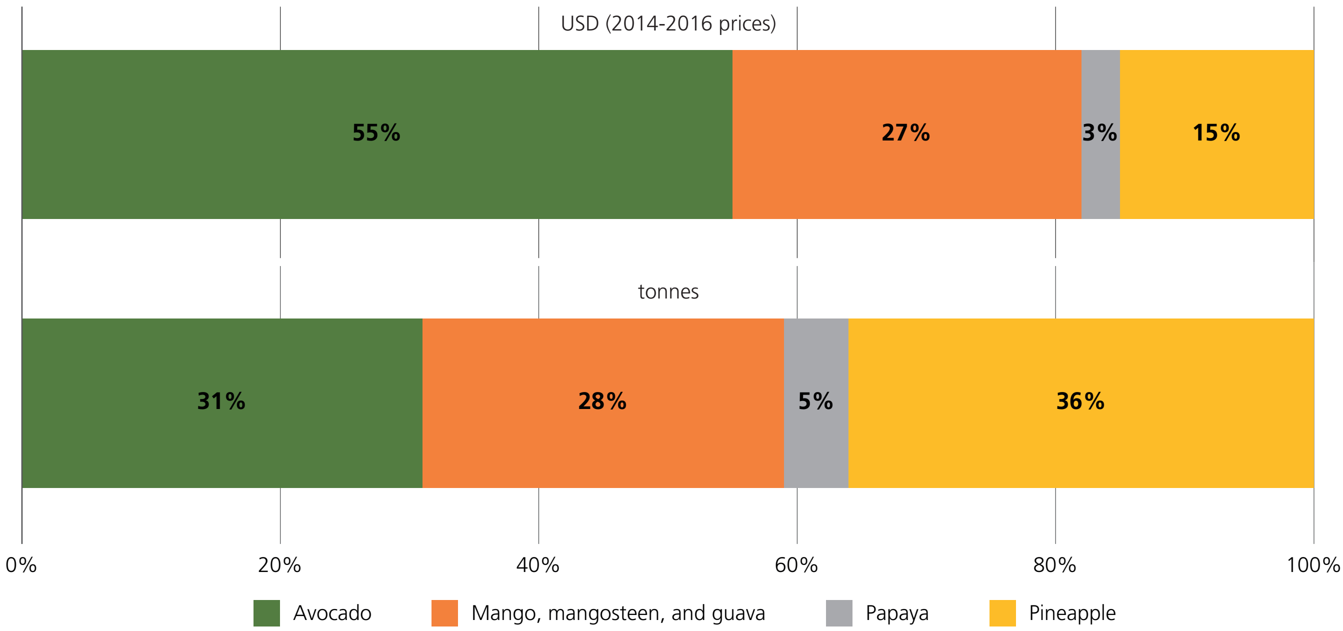
The leading exporters of major tropical fruits including avocados are concentrated in Latin America and the Caribbean (FAO, 2019b, 2022d). Large volumes of tropical fruits are shipped from the region, predominantly to the United States of America and the European Union, the biggest importing regions globally. However, the availability of product for export is highly dependent on seasonal climatic conditions in producing countries. In the future, consumers in developed countries may suffer as a result of an over-reliance on climate vulnerable countries for their supplies of fresh fruit and vegetables. This may have potentially negative consequences for the availability, price and consumption of fruit and vegetables in countries such as the United Kingdom, where an estimated 70 percent of fruits available for purchase are imported from outside of the European Union (Frankowska, Jeswani and Azapagic, 2019). Thus, disruptions to the supply of fruits due to climatic effects in producing countries has the potential to affect the dietary intake and health of consumers in importing markets, particularly of older people and low-income households (Scheelbeek *et al.*, 2020).

In addition, countries which have typically exported tropical fruits in the past, and who rely on these exports for foreign income and employment creation, many now face new competitors for import markets due to global warming. Countries that had a temperate climate could become increasingly capable of producing such fruits. As a result, current tropical fruit producers may need to explore possibilities of expanding their domestic and regional markets to reduce the risks associated with increasing competition for international markets from non-traditional producer countries (Liu, 2017). Likewise, current producers may be motivated to defy their production possibility frontier by expanding into new production areas or shift production locations to find more suitable agroclimatic conditions to ensure they continue meeting market demands. Such practices can also exacerbate climate risks by degrading vital natural resources (soil, water and forests) and ecosystems. **More specifically, what does this mean for production and export of avocados?**

1.3 Avocados as important tropical fruit exports at risk of climate change impacts

Global demand for the major tropical fruits remains strong despite significant bottlenecks in global supply chains and rising input and transport costs. Pineapple, avocado and mango continue to be the three most significantly traded tropical fruits in terms of their export quantities, bananas aside.

Figure 1. Major tropical fruits: Share of 2022 (preliminary) export quantities by type, measured in USD billion, constant dollar (2014–2016) and tonnes



Source: **FAO.** 2023a. *Major Tropical Fruits Market Review. Preliminary results 2022*. Rome.

Global exports of avocado rose by 9.7 percent, to 2.5 million tonnes in 2021, reaching a historical peak. Avocados are the second most popular tropical fruit for export after pineapple, however, in value terms, avocados account for over 50 percent of global trade in major tropical fruits, due to the significantly higher average export unit value of this fruit (**Figure 1**). On the demand side, global shipments of avocado to the United States of America and the European Union are being driven by increasing consumer awareness of health consciousness and the nutritional benefits of avocados, encouraged by national and retail level advertising campaigns to increase consumption. This strategy has proved particularly effective for growing the demand for avocados, despite rising costs of production, transport and marketing along the value chain (FAO, 2022e).

Against this background of strong international demand for avocados, in **Chapter 2** we discuss climate trends facing the major avocado producing and exporting countries around the world. Predicted climate effects over the coming decades suggest that production is likely to become more challenging in the future, particularly if adaptation and mitigation measures are not urgently adopted within the coming years. Many countries are already seeing the negative impacts of climate change and extreme weather events on production. For example, in 2020, severe drought conditions experienced in central Chile hampered avocado exports, and similarly, a persistent heat wave and water scarcity in Israel reduced the quantity and quality of the country's avocado harvests, with a decline of almost 50 percent on exports from 2019 (FAO, 2021e). More frequent extreme weather events such as hailstorms have also severely damaged avocado harvests available for export from countries such as Mexico and South Africa in recent years.

Preliminary results for 2022 suggest that the volume of world trade in major tropical fruits looks likely to fall to USD 9.9 billion in constant 2014–2016 dollar terms, marking a decline of 5 percent from 2021 (FAO, 2023a). This would constitute the first significant contraction of trade in the global market for tropical fruits. Preliminary data indicate that shortages in global supplies associated with adverse weather, persisting bottlenecks in global supply chains as well as high input and transport costs have contributed to the decline. For avocados, adverse weather conditions, in particular cooler than normal temperatures, resulted in production declines from several major tropical fruit production zones, most notably a steep fall in avocado supplies from Mexico (FAO, 2023a). Building the sustainability and resilience of tropical fruit value chains to environmental, economic and social shocks has never been more important to ensure production and trade of these important commodities.

1.4 The Responsible Fruits Project and the FAO Strategy on Climate Change

The development of this technical guide is an output of the Responsible Fruits Project. In 2019, the Markets and Trade Division of the United Nations Food and Agriculture Organization embarked on a global project titled "Building responsible global value chains for the sustainable production and trade of tropical fruits" (also known as the "Responsible Fruits Project"). The project works with businesses, farmer organizations and other actors in the avocado value chain, with the aim to improve business performance by helping this value chain be more sustainable and more resilient. The project builds on more than a decade of FAO experience working with the private sector on tropical fruits.[4] The outcome of this project will be a network of companies committed to improving their resilience and the environmental, social and economic impacts of their operations and those of their suppliers.

The project aims to help companies operating in avocado supply chain to strengthen or establish risk-based due diligence systems that will make their operations more sustainable and resilient to shocks. It also provides a confidential environment for peer learning on pre-competitive issues through peer learning webinars and other knowledge sharing and capacity development events. This guide is part of a series of demand-driven guides[5] to be developed by the project on specific technical challenges determined by project participants.

A baseline survey conducted by the project in 2021 highlighted climate change impacts as the number one sustainability challenge facing avocado companies. This finding was further confirmed in 2022, when the project conducted an online survey on resilience and asked avocado companies to identify the main issues increasing the susceptibility of their operations to suffer from external shocks. Avocado value chain actors considered environmental and climatic factors as the main drivers of vulnerability in their businesses (75 percent of avocado actors surveyed). On this basis, the topic of climate change adaptation was selected in partnership with project participants as a suitable topic for this technical guide.

This guide is aligned with the FAO Strategy on Climate Change (FAO, 2022c), which focuses on enhancing capacities to implement nationally determined contributions under the Paris Agreement.[6] The Strategy supports countries to adapt to and mitigate the effects of climate change through research-based programmes and projects geared towards adapting smallholder production and making the livelihoods of rural populations more resilient. The Strategy moves away from a reactive response to crises to proactively preventing and anticipating them, supporting people before, during and after shocks. The Strategy focuses on a) giving a leading voice to farmers and other agriculture-dependent communities in the development of adaptation strategies, b) fostering horizontal and vertical integration and c) promoting transformative change. By implementing this Strategy, FAO aims to support member countries in their efforts to implement climate change adaptation and mitigation practices, while working towards climate-resilient and low-emission agrifood systems that strive to achieve the Sustainable Development Goals, in particular eradicating hunger and malnutrition. As noted earlier, tropical fruits play an important part in a healthy diet. This guide aims to contribute

[4] This includes facilitating the World Banana Forum, the banana sector's premier multistakeholder platform, and work with over 30 leading agrifood enterprises and industry associations to apply the risk-based due diligence recommendations of the OECD-FAO Guidance for Responsible Agricultural Supply Chains.

[5] The first technical guide titled "Gap analysis to support due diligence in the avocado and pineapple sectors is available here.

[6] The Paris Agreement requires each Party to outline and communicate their post 2020 climate actions to reduce greenhouse gas emissions and adapt to the impacts of climate change through nationally determined contributions (NDCs).

towards this strategy by proactively increasing the awareness of producers and exporters of avocados to climate related risks and sharing adaptation strategies as described below.

1.5 Purpose of the guide and who is it for?

The purpose of this technical guide is to:

- provide up-to-date information on recent and predicted climate change effects and trends in key avocado producing and exporting countries;
- identify climate change risks and impacts on the production and trade of avocado;
- identify adaptation practices and recommendations that may help to address these risks, minimise negative impacts and build resilience;
- share good practices adopted by companies to address specific climate-related production risks in a sustainable manner; and
- identify gaps in information, research and technical solutions needed to strengthen the availability and adoption of adaptation practices.

The guide is for producers and exporters of avocado who are interested in learning more about climate change in the context of their own business systems. It is anticipated that for many producers and exporters, this guide may be a starting point for stimulating discussion and future research on national and region-specific climate change impacts on avocado production, and joint planning on adaptation solutions to support the long-term sustainability of the export industry. Although the guide is focused on adaptation, it should be noted that adaptation and mitigation efforts to reduce GHG emissions go hand-in-hand, and mitigation strategies can also be designed in a way to contribute to and reinforce adaptation. For example, strategies to enrich carbon content in agricultural soils have the potential to deliver strong mitigation outcomes, while at the same time soils that manage to build organic carbon by minimizing tillage, erosion and chemical use also improve crop production and profitability (Scherr and Sthapit, 2009 in Bioversity, 2014).

The practices selected are also aligned with FAO's work on sustainability, by promoting techniques, technologies and actions that enable transformation of value chains towards green and climate resilient practices. These include agroecology, climate-smart agriculture, conservation and digital agriculture.

1.6 Methodology and limitations of the guide

This guide was developed through a consultative process with avocado companies participating in the Responsible Fruits Project. In June 2022, the project held a webinar to introduce the topic and discuss what climate change means to avocado companies. Avocado companies shared their experiences of recent impacts of climate change on production systems during a panel session, followed by a lively discussion session. The purpose of the guide was introduced and agreed upon, and participants were invited to register their interest to join a working group on climate change adaptation to develop the guide.

Four online working group sessions were held in support of the guide:

- Working group 1 Session on 13 Oct 2022 with participants in Latin America to identify climate risks and impacts on production.
- Working group 2 Session on 24 November 2022 with participants in Asia in partnership with the International Tropical Fruit Network (TFNet) to identify climate risks and adaptation practices for pineapple production.
- Working group 3 Session on 30 November 2022 with participants in Latin America to identify and discuss adaptation practices.
- Working group 4 Session on 13 April 2023 to present the draft guide and validate the draft chapters 4 on adaptation practices with all participants involved in the Responsible Fruits Project.

In addition to the inputs from the working group members, the drafting of the guide has been supported by key informant interviews with individual companies, research institutions and with climate change focal points from FAO Country Offices in regions and countries where avocado production and export are important. These interviews helped to develop the company adaptation practice examples given in **Chapter 4**, and to determine relevant projects and research outputs produced by FAO Country Offices or their research partners. An extensive review of the literature was also conducted covering FAO publications on climate change, reports from international agencies working on climate change (e.g. IPCC, World Bank, OECD, CIAT), scientific journals on agronomic practices and impacts of climate change on tropical fruit production in general, and avocado production specifically.

What the guide is and is not: some limitations

During the working group sessions, the limitations of the guide were discussed with participants. Given the timeframe to develop the guide and the global nature of the Responsible Fruits Project, it was not possible to conduct the field-based, longitudinal scientific research that may be needed to answer specific questions related to climate change impacts over time on avocados under various production conditions. On this basis, the guide is not intended to be a comprehensive scientific guide with prescriptive adaptation solutions to fit all contexts. Rather, it aims to highlight the climate related risks and challenges producers in certain countries are facing, and the adaptation solutions they are trialling to minimize future risks. Additional review of the scientific literature has been conducted to further validate the adaptation practices identified by companies. The guide also recognizes that adaptation efforts require the collaboration among different state and non-state actors to be sustainable in the long term.

1.7 Structure of the guide

Chapter 1 introduces the background to the guide and discusses the impact of climate change on global agriculture and tropical fruit production. It also explains the purpose and limitations of the guide.

Chapter 2 explains the scope of the guide, including the countries selected for further investigation into the impacts of climate change on avocado production; the climate trends affecting these countries; and a brief overview of some of their experiences to date in developing National Adaptation Plans for the agriculture sector.

Chapter 3 introduces the climate risks facing avocado production across a range of countries and discusses the impact of these risks on production.

Chapter 4 presents and discusses climate change adaptation strategies for avocado production.

Chapter 5 discusses some of the challenges in identifying climate risks and adaptation solutions, and identifies gaps in information, research and technical solutions that need to be addressed to strengthen the availability and adoption of adaptation practices.

Annex 1 provides a list of additional resources that may be of use to those companies who are interested in learning more about climate change and its impacts on agriculture, tropical fruit and adaptation options.

Chapter 2.

Scope of the guide

As discussed in **Chapter 1**, climate change is affecting countries and regions differently, and therefore, for a guide on adaptation to be meaningful, some further investigation into country-specific climate trends and national adaptation strategies is required. Given the global focus of the Responsible Fruits project on **sustainable production and trade** of avocado, the selection of countries for further investigation in this guide has been guided by their relative importance in **global production and export** as an important source of foreign income and employment. On this basis, six avocado producing and exporting countries have been selected for deeper analysis as discussed below.

It should be noted that production of avocado in other major producing countries that were not selected, such as Indonesia and the Dominican Republic, will also be affected by climate change in the future. This may result in reduced availability of the fruit for domestic consumers as the major outlet for their production, or excess supply depending on the fluctuations of climatic conditions from year-to-year. Therefore, the guide may also be of interest to producers in those countries that are facing similar climatic threats regardless of their engagement in the export sector.

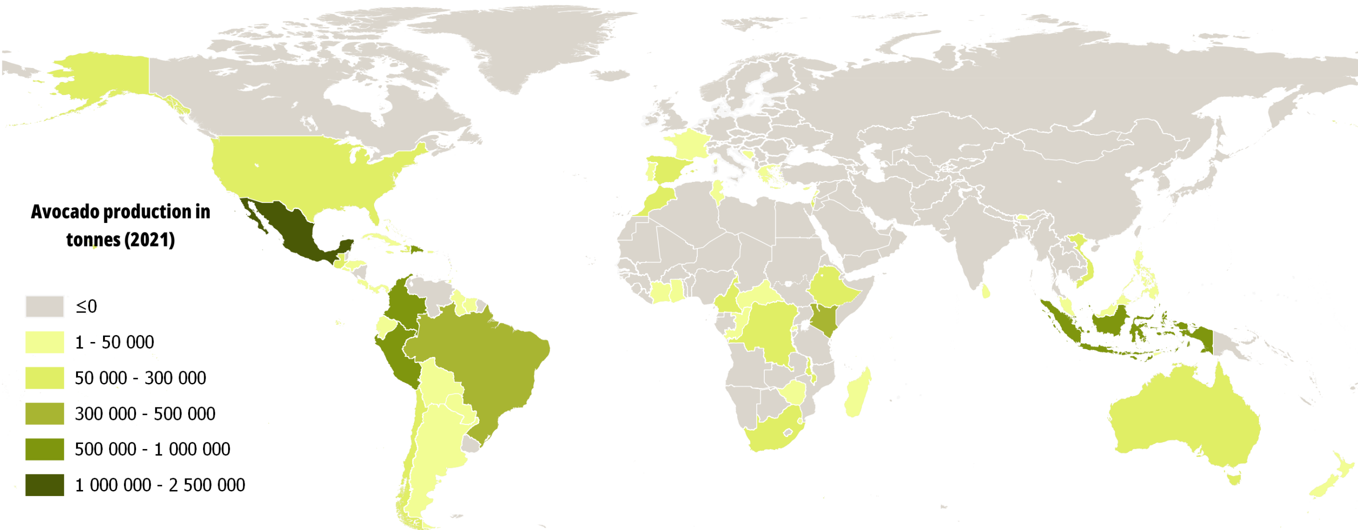
2.1 Avocado production and export

2.1.1 Global production of avocado

According to FAOSTAT, avocado is produced in more than 60 countries around the world. Global production of avocado has expanded rapidly over the past two decades, from approximately 2.9 million tonnes in 2002 to 8.7 million tonnes in 2021, representing an average annual growth rate of almost 10 percent. As discussed in **Chapter 1**, much of this growth in production has been driven by increased incomes and awareness of healthy diets, with growing consumption of avocado in domestic and export markets.

As seen in **Figure 2**, the production of avocado is highly concentrated in the Latin America and the Caribbean region. In 2021, almost 70 percent of global production came from the region. Mexico is the leading producer, accounting for 28 percent of global production, and other major producers in the region include Colombia accounting for 11 percent, Peru with 9 percent and the Dominican Republic with 7 percent (FAO, 2023b). Other large global producers outside of the region include Indonesia, where production is focused solely on the domestic market, and Kenya, where production has grown to meet import demand primarily in the European Union.

Figure 2. Map of global avocado production distribution



Source: Authors' own elaboration based on **FAO.** 2023. FAOSTAT: Crops. In: *FAO*. Rome. [Cited 21 March 2023]. www.fao.org/faostat/en/#data/QC

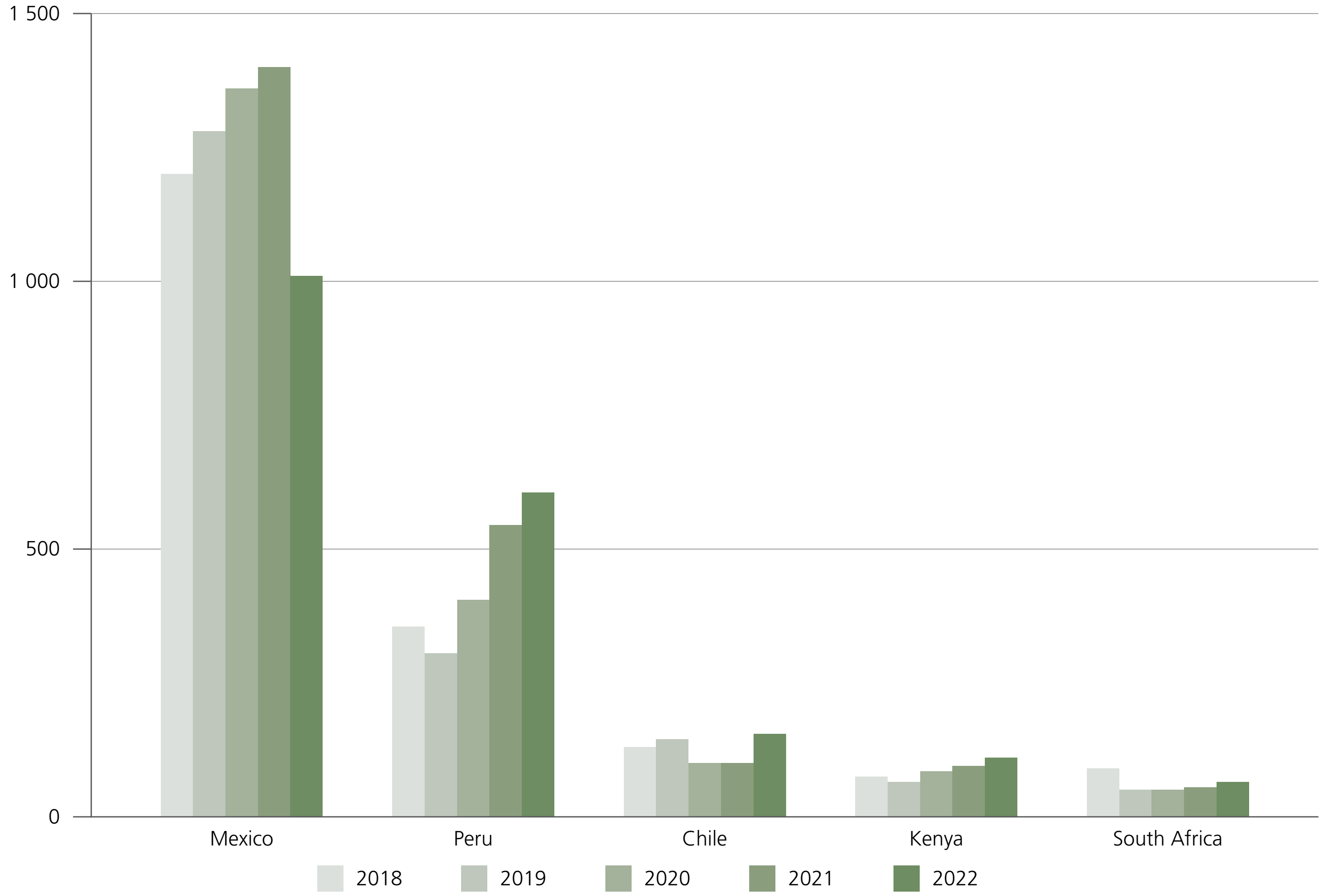
2.1.2 Global trade of avocado

In 2021, global exports of avocado reached a historical high of 2.5 million tonnes (FAO, 2022e). Mexico, as the world's leading producer of the market-preferred Hass variety avocado, exported approximately 1.4 million tonnes, accounting for 56 percent of total exports, followed by Peru with 542 000 tonnes or 22 percent of global exports (FAO, 2022d). However, in 2022 global avocado exports are expected to decline by approximately 6 percent, to below 2.4 million tonnes, mainly linked to severe weather-induced supply shortages in Mexico (FAO, 2023a).

For Mexico, the United States of America represents the major destination market, absorbing 93 percent of total exports in 2021; for Peru the major destination markets are more diverse, yet with approximately 46 percent of exports destined for the European Union (FAO, 2022d). **Figure 3** highlights the five leading exporters during the five-year period from 2017–2022 and their respective quantities (preliminary data for 2022). Colombia is also one of the fastest growing producers and exporters of avocado, with exports increasing by more than 500 percent from 18 727 tonnes in

2017, to 95 773 tonnes in 2021, making Colombia the fourth most important exporter of avocados in 2021, after Chile (overtaking Kenya).

Figure 3. Avocado export quantities from the leading exporters 2018–2022 (preliminary data for 2022)



Source: **FAO.** 2023. *Major Tropical Fruits Market Review – Preliminary results 2022*. Rome.

2.1.3 Country selection for the guide

Based on the above discussions, six countries were selected for further investigation into climate change effects and adaptation strategies: **Mexico, Peru, Chile, Colombia, Kenya and South Africa**. However, where possible, relevant scientific literature has also been consulted and integrated from other avocado-producing nations to identify innovative adaptation solutions, with useful findings emerging from countries such as Australia, Israel, Morocco, New Zealand and Spain.

2.2 Climate trends affecting key producing and exporting countries

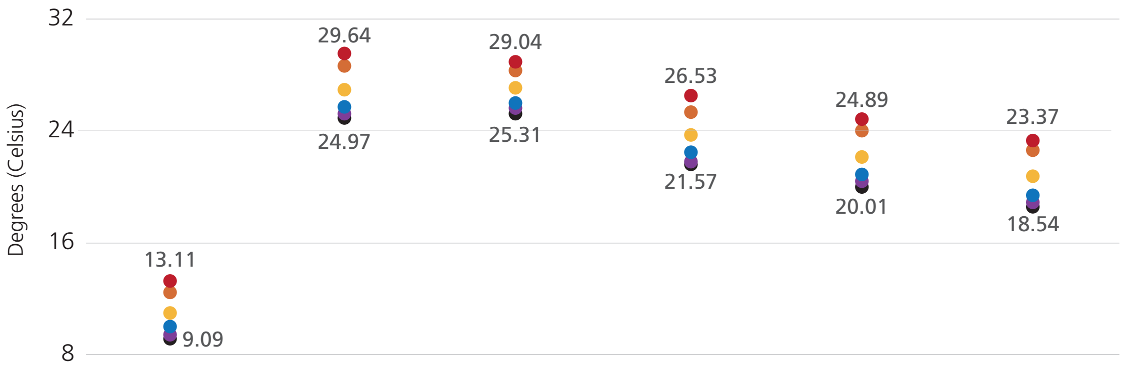
As discussed in **Chapter 1**, tropical fruits are highly sensitive to changes in environmental factors including **temperature** and **precipitation**, which have a direct correlation with the regulatory physiological stages of fruit trees. The quality and quantity of avocado production may be negatively affected by increased temperatures and changes in precipitation (e.g. reduced water availability/ excessive rainfall) associated with climate change. This section provides high-level information on country-level baseline climate trends associated with temperature and precipitation. It also provides information on future projections according to data from the World Bank Climate Risk Country profiles and general country-level data available on the World Bank Climate Change Knowledge Portal. The specific climate risks identified by avocado producers and companies participating in the Responsible Fruits Project are discussed in detail in **Chapter 3** (climate risks facing avocado production).

2.2.1 Climate trends associated with temperature

The World Bank estimates that average temperatures in all of the major avocado producing countries selected in this guide will increase across all of the five emissions scenarios modelled under climate change (**Figure 4**).[7] For example, considering a middle scenario (SSP2-4.5), where CO_2 emissions start to decrease after 2050, temperature in South Africa is expected to increase by 2.20 °C from 2014 to 2100. Mexico (2.16 °C), Peru (2.14 °C) and Colombia (2.04 °C) closely follow these trends. Chile and Kenya are projected to see a rise in temperatures by 1.76 °C and 1.80 °C respectively, by the end of the century. Considering a more pessimistic scenario (SSP5-8.5), temperatures in all the six countries are projected to surpass 3.7 °C by 2100.

[7] The World Bank estimated future mean temperatures until 2100 by using five possible future scenarios that consider the levels of emissions and the Shared Socioeconomic Pathways (SSPs) model. Each scenario analyses countries' emissions, mitigation efforts and development, using average temperatures between 1995 and 2014 as the reference period. The models are SSP1-1.9: Most optimistic scenario, describing a world where global CO_2 emissions are cut to net zero by 2050. SSP1-2.6: Net-zero is reached after 2050 and temperatures stabilize around 1.8 °C higher by 2100. SSP2-4.5: CO_2 emissions start to decrease after 2050 and do not reach net-zero by 2100. Progress toward sustainability is slow, with uneven development and income growth and temperatures rise 2.7 °C by 2100. SSP3-7.0: CO_2 emissions roughly double from current levels by 2100 and temperatures rise by 3.6 °C by 2100. SSP5-8.5: Current CO_2 emissions levels almost double by 2050. The global economy grows quickly relying on fossil fuels and leading energy-intensive lifestyles; the average global temperature is 4.4 °C higher.

Figure 4. Mean temperatures projected by 2100, by SSP model and avocado producing country



	Chile	Colombia	Kenya	Mexico	Peru	South Africa
● Reference year (1995—2014)	9.09	24.97	25.31	21.57	20.01	18.54
● SSP1-1.9	9.24	25.30	25.62	21.75	20.42	18.89
● SSP1-2.6	9.78	25.75	26	22.44	20.87	19.32
● SSP2-4.5	10.85	27.00	27.11	23.73	22.15	20.74
● SSP3-7.0	12.33	28.72	28.38	25.34	24.06	22.60
● SSP5-8.5	13.11	29.64	29.04	26.53	24.89	23.37

Note: Chile's large climate diversity among regions – from tropical in the north, Mediterranean in the center, and Antarctic (antiboreal oceanic) in the South – skew down the average temperatures as shown in the figure and compared to other countries.

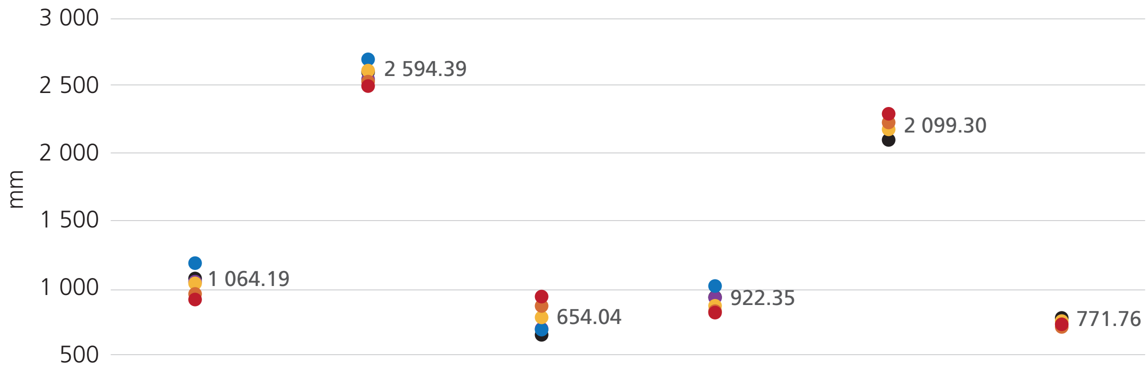
Source: Authors' own elaboration with data from **World Bank.** 2022. Climate Change Knowledge Portal for development practitioners and policymakers. In: World Bank Group [online]. Washington. [Cited 7 October 2022]. https://climateknowledgeportal.worldbank.org

According to the IPCC, an increase of 2 degrees will produce more frequent and intense extreme weather (augmented droughts, heavy rains and hailstorms), the extinction of some animals and plants, and will put the production of some agricultural commodities at risk (IPCC, 2021).

2.2.2 Climate trends associated with precipitation

Precipitation variability (distribution, frequency and quantity during the year) and long-term changes have differentiated effects on avocado production, depending on whether water deficit or excess is experienced at specific stages of the plant development. Unlike temperature trends, future precipitation patterns do not show a clear trend and vary depending on the region and producing country (**Figure 5**).

Figure 5. Projected precipitation by 2100, reference period 1995–2014, for avocado producing countries

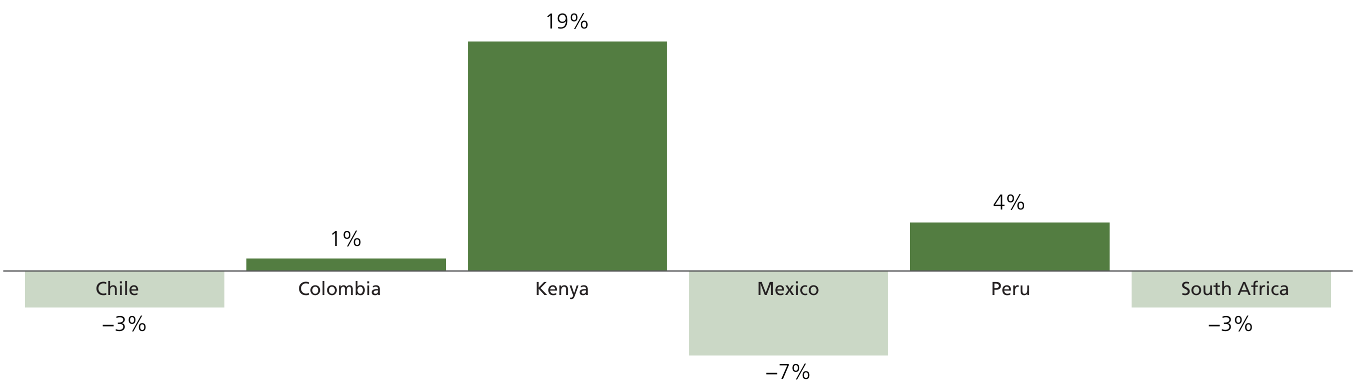


	Chile	Colombia	Kenya	Mexico	Peru	South Africa
● Reference year (1995—2014)	1 064.19	2 594.39	654.04	922.35	2 099.30	771.76
● SSP1-1.9	1 188.87	2 699.55	772.84	1 018.45	2 197.95	740.87
● SSP1-2.6	1 047.88	2 603.19	688.57	932.50	2 175.77	742.59
● SSP2-4.5	1 031.69	2 613.60	778.99	861.87	2 188.58	748.48
● SSP3-7.0	955.03	2 535.86	866.46	824.07	2 228.75	711.37
● SSP5-8.5	912.57	2 503.00	933.61	815.16	2 295.73	731.27

Source: Authors' own elaboration with data from **World Bank.** 2022. Climate Change Knowledge Portal for development practitioners and policymakers. In: World Bank Group [online]. Washington. [Cited 7 October 2022]. https://climateknowledgeportal.worldbank.org

For avocado producing countries, Colombia, Kenya and Peru have a projected increase in rainfall by 2100 considering the SSP2-4.5 scenario. Kenya is expected to see the largest increase in precipitation by 19 percent, followed by Peru (4 percent) and Colombia (1 percent). Mexico is projected to experience the sharpest decline in rainfall by 7 percent by the end of the century, followed by Chile and South Africa (3 percent each) (**Figure 6**).

Figure 6. Precipitation change rate by 2100 using the SPSP2-4.5 model in avocado producing countries



Source: Authors' own elaboration.

To zoom in further on the climate trends discussed above from a national perspective, **Table 2** summarizes the climate baseline and future projected temperature and precipitation trends affecting the selected avocado producing countries according to the World Bank Climate Risk Country data and profiles for 2021 (World Bank, 2022). It should be noted that these trends are mostly reported at national level, which may/may not account for regional and local microclimate differences in key producing areas. Information on the location of avocado[8] producing regions within these countries is noted for reference. Localized climate risks identified by producers involved in the Responsible Fruits Project are discussed in **Chapter 3**.

Table 2. Overview of temperature and precipitation trends associated with climate change in selected avocado producing countries

Country	Temperature projections	Precipitation projections
Mexico	Mexico has the world's largest avocado cultivation area. Production for export occurs in the state of Michoacan (75 percent of planted land area) and adjoining state of Jalisco (15 percent), both located along the Pacific Coastline (HAB, 2019a).	
	• Temperatures are expected to increase between 2.5 and 3.5 °C by 2100. The northern part of the country is expected to see an increase in average temperatures by 4 °C. • An average temperature increase by 1.4 °C is projected in Michoacán by 2100, considering a moderate scenario, and up to 4.7 °C under a pessimistic scenario (INECC, 2021). In Jalisco, temperatures are predicted to rise by an average of 3.7 °C by 2100 in a middle scenario, and 4.8 °C in the pessimistic scenario.	• Rainfall is expected to reduce by an average of 5–10 percent (between 22 to 45 mm less per month). • The largest share of the country is projected to become dryer, experiencing more frequent droughts. • States on the north-east Pacific coast and the North Atlantic coast regions will see an increase in precipitation, associated with higher number and intensity of cyclones. This is accompanied by a higher risk of floods and landslides, especially in lowland areas, and already experienced in Michoacán and Jalisco.
Peru	Avocado production is mainly concentrated in the 2 000 km dry coastal strip from Chiclayo in the north to Arequipa in the south (HAB, 2019b).	
	• The average temperature is expected to rise between 2 °C and 6 °C for medium and high emissions scenarios, respectively in the 2036–2065 period. • Models indicate that the rise in minimum temperatures will be higher than in maximum temperatures in both scenarios. • La Niña events will likely continue having an increasing trend in the future.	• Since 1970, Peru has lost more than 40 percent of its glacier surface, affecting river levels feeding from it. The average runoff in rivers in the Sierra and Selva is expected to decrease by up to -52 percent, in mid and high emissions scenarios. Rivers in the Costa region are expected to be more affluent (up to 1 000 percent in a month). • El Niño will increase the incidence of flood and drought events in the Costa and Sierra regions, respectively, and creating the conditions for pest development in both dry and humid areas.

8 Information on production areas for avocado has been sourced primarily from the Hass Avocado Board's (HAB) Country Profile Reports where available https://hassavocadoboard.com/types/country-profile

Country	Temperature projections	Precipitation projections
Chile	Avocados are produced in both the coastal zone and the inland zone, with production concentrated in the central part of the country over approximately 500 km between Vicuña in the north (mid-north of Region IV) and Peumo (north of Region VI) (HAB, 2020)	
	• Average annual temperatures are expected to increase by 1.4 °C to 1.7 °C by mid-century and by as much as 3 °C to 3.5 °C by 2100. • Regional climate models project that temperature increases will be highest in the central regions, where avocados are grown. • The number of frost days (Tmin<0 °C), is projected to decrease by 12–42 days by the 2050s. The number of summer days (Tmax>25 °C) are expected to begin earlier and increase by 2 to 27 days by the 2050s.	• Precipitation in Chile is projected to decrease consistently by 1.5 mm to 9.3 mm per month by the 2050s, and to 5.5 mm to 11 mm by 2090. • Chile's central region is expected to experience significantly higher reduction in precipitation than other regions. • Increased heat and water scarcity conditions are likely to increase evapotranspiration and reduce soil moisture.
Colombia	Avocado cultivation is primarily concentrated in the central ranges, between the North of Cauca Department and Antioquia Department (HAB, 2022b).	
	• The number of very hot days (temperatures above 35 °C) are projected to increase from approximately 16 to 131 days of the year by the end of the century. • Glacier loss is expected to continue, with critical consequences for water availability.	• More frequent floods and cooler weather will occur, associated with La Niña events. • Highly specialized niche crops such as coffee, cocoa, and other fruits will likely see critical changes in the prevalence of pests and diseases due to increased rainfall and humidity.
Kenya	Avocado production occurs in five main counties. Most production (40 percent) occurs in Murang'a county located in the central region of Kenya, followed by Nyeri, located in the central highlands. Other regions growing avocado include Kiambu, Kisii, Meru and the entire Mt. Kenya region (avodemia; Avocado Society of Kenya).	
	• Temperatures are projected to continue rising by 1.7 °C by the 2050s and by approximately 3.5 °C by 2100. • The number of hot days and nights will increase, with hot days projected to occur on 19 to 45 percent of days by mid-century. Hot nights are expected to increase more quickly, projected to occur on 45 to 75 percent of nights by mid-century.	• Extreme rainfall events are predicted to increase in frequency, duration and intensity, with associated increased risk and intensity of floods, mudslides and landslides. • Climate variability will also further drought likelihoods for some regions. • Some regions of Kenya may see a benefit from a changing climate, specifically the temperate and tropical highlands.

Country	Temperature projections	Precipitation projections
South Africa	Avocado production has traditionally been concentrated in Limpopo and Mpumalanga provinces in the Northeast of the country. However, due to growing global demand and to produce year-round, production is expanding in KwaZulu-Natal and the Eastern and Western Cape provinces (SAAGA, 2023)	
	• Rising temperatures are expected to continue, with mean monthly temperatures projected to rise 2.0 °C by the 2050s and 4.2 °C by the 2090s, under a high-emission (business-as-usual) scenario. • By mid-century, the Northern Cape, Northwest and Limpopo will all likely see an increase of hot days (Tmax>35 °C) of 20 and 40 days per year; meaning more than 120 days per year across the country's interior by 2100. • As temperatures rise, more intense heat waves and higher rates of evapotranspiration will follow, affecting agricultural productivity.	• Rainfall projections remain uncertain, yet a majority of models point to annual rainfall declines for the country. • Water scarcity is expected to increase, impacting the central, northern and southwestern regions. • Future flood risk is also likely to increase, particularly in KwaZulu-Natal, the Eastern Cape and Limpopo. • Changing rainfall patterns will significantly alter agricultural productivity and shift harvest seasons, increase soil moisture deficits.

Source: Climate trend data and descriptions extracted from **World Bank** (2021) and **World Bank** (2022). Information from Mexico was also retrieved from **CEDRSSA.** 2020. *Impacto económico del cambio climático en México*. Mexico. For Peru, **Ministerio del Ambiente.** 2016. *Tercera Comunicación Nacional del Perú a la Convención Marco de las Naciones Unidas sobre el Cambio Climático*. Peru.

2.3 Nationally determined contributions and the importance of National Adaptation Plans for the agriculture sector

In line with the above discussion on national level climate trends, it is important to understand how countries are planning and coordinating their efforts to address climate change through actions to reduce GHG emissions and implement adaptation plans. At an international level, the foundation for these actions stems from the Paris Agreement, which was signed by 196 countries on 12 December 2015 in Paris, France at the UN Climate Change Conference of Parties (COP21). The Paris Agreement is a **legally binding international treaty on climate change**. It entered into force on 4 November 2016. All six countries covered in this guide are signatories to the Agreement. Its overarching goal is to hold "the increase in the global average temperature to well below 2 °C above pre-industrial levels" and pursue efforts "to limit the temperature increase to 1.5 °C above pre-industrial levels" (UNFCCC, 2023). The Paris Agreement also includes the Global Goal on Adaptation, which aims "to increase the adaptive capacity, strengthen the resilience and reduce vulnerability to climate change, to contribute to sustainable development and ensuring an adequate adaptation response" (UNFCCC, 2015). In recent years, world leaders have stressed the need to limit global warming to 1.5 °C by the end of this century. According to the IPCC, crossing the 1.5 °C threshold risks unleashing far more severe climate change impacts, including more frequent and severe droughts, heatwaves and rainfall. To achieve this, GHG emissions must peak before 2025 at the latest and decline 43 percent by 2030 (IPCC, 2023).

Implementation of the Paris Agreement by each signatory is achieved through national climate action plans known as nationally determined contributions (NDCs), which outline the efforts made by each country post-2020 to reduce national GHG emissions and adapt to the impacts of climate change. Each country must set targets for reduction of GHG emissions, outline how they plan to achieve these through mitigation measures, and describe their strategies for implementing adaptation practices across prioritized sectors. NDCs are submitted every five years to the United Nations Framework Convention on Climate Change (UNFCCC) secretariat. In order to enhance the ambition over time, the Paris Agreement states that successive NDCs must represent a progression compared to the previous NDCs and reflect its highest possible ambition. The NDCs serve as a collective way to track global progress on climate goals and signal whether global warming can stay well below the threshold of 1.5 °C. All six countries covered by the guide have submitted NDC reports[9] to the UNFCCC since 2020.

A review of these reports indicates that mitigation targets and specific programmes to reduce emissions remain the focus of NDCs. While adaptation efforts are mentioned across the six reports, in most cases these are in more general/abstract terms than those related to mitigation, with unclear indication of how these efforts will be monitored and measured. These findings were also confirmed in the UNFCCC 2022 NDC Synthesis Report which reviewed 166 of the NDCs including 142 new or updated NDCs, as well as by the 2023 NDC Global Update Report. These reports found that while the adaptation component in the updated NDCs had improved, further work is still needed to introduce time-bound quantitative adaptation targets and the associated indicator frameworks across all reports. One of the challenges to encouraging greater clarity on adaptation strategies and targets, is the lack of a standardized reporting framework for adaptation in the NDCs. Some countries have clearly defined their adaptation programmes and begun to set targets in their NDCs (e.g. Kenya), while others remain more abstract.

The development and implementation of National Adaptation Plans (NAPs) is an important instrument to operationalize the implementation of adaptation goals included in the NDCs. Climate change adaptation in the agriculture sectors is among the foremost priorities identified in developing countries' national climate plans. More than 95 percent of developing countries that specified adaptation priorities and/or actions in their NDCs referred to the agriculture and land use sectors, with 78 percent referring to specific actions related to ecosystems and natural resources (FAO, 2016, 2017a; Crumpler *et al*, 2021). However, these plans are often weak when it comes to the detail on how efforts will be targeted towards supporting adaptation in agriculture. They may not cover critical aspects of adaptation planning needed not only to support agriculture (including crop and

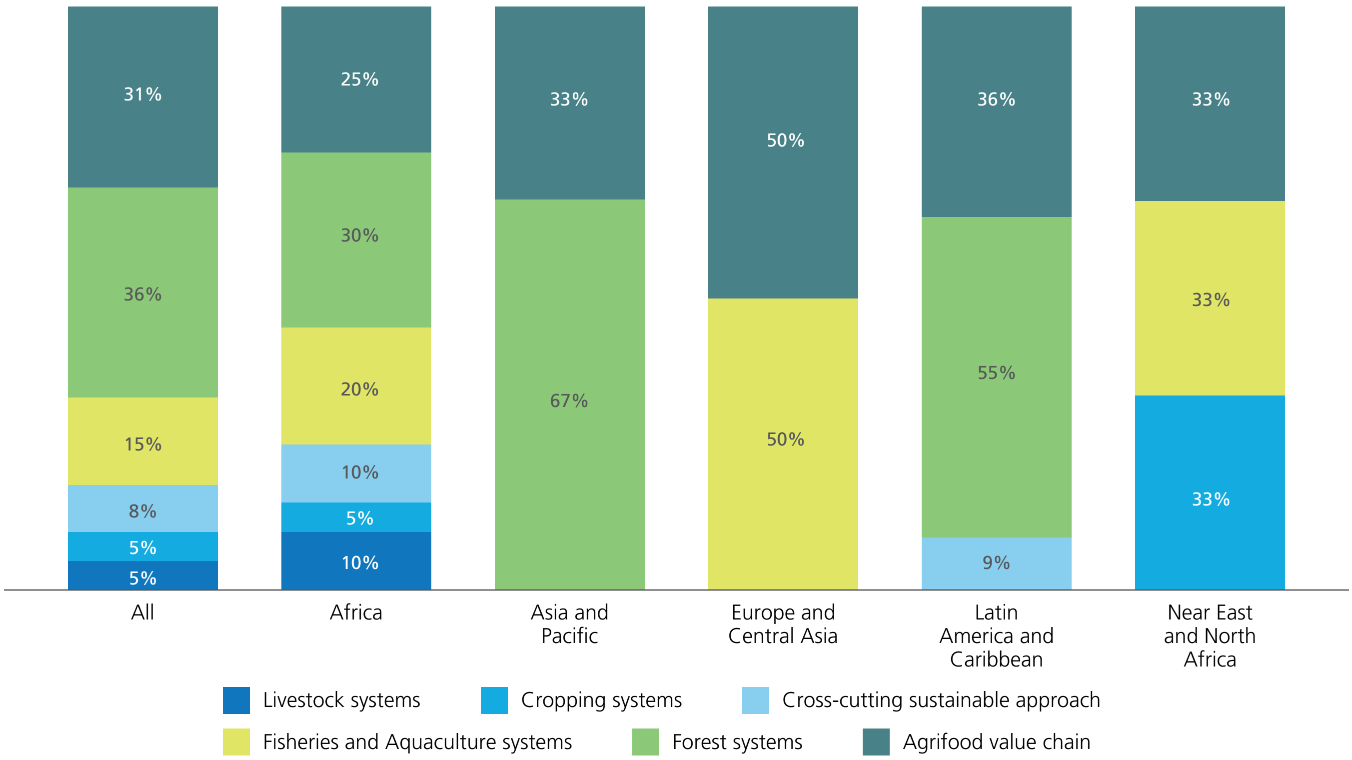
9 NDC reports for all countries covered by the guide are available at the NDC Registry managed by UNFCCC. Reports are available for Chile, Colombia, Kenya, Mexico, Peru and South Africa.

livestock production, fisheries and forestry) but also food security and nutrition. In addition, a gender-responsive approach is also needed in NAP-Agriculture planning to recognize the disproportionate impact of climate change on the livelihoods of women, girls and youth, and begin to address the structural inequalities (e.g. in policies, laws, norms, institutions, etc.) that underlie many of the different adaptation challenges that women and men may experience (FAO, 2018a).

NDCs and NAPs also recognize the critical need to involve private companies in the agriculture and land use sectors. A recent analysis on the NDCs and NAPs submitted to date indicate that while 60 percent of countries engage in consultations with the private sector in the NDCs planning process, only 10 percent have active collaboration (Crumpler *et al.*, 2021). This trend is observed across all regions, though the Latin America and Caribbean region shows the greatest active collaboration between governments and the private sector in the NDCs planning (*ibid.*).

The main entry points for climate action dialogue across all regions are linked to mitigation and/or adaption potential in forest systems (36 percent) and agrifood value chains (21 percent; see **Figure 7**), both of great relevance to the avocado industry operating in the countries selected for analysis in this guide.

Figure 7. Private sector entry-points in the NDCs planning related to the agriculture sectors, by region and subsector



Source: **Crumpler, K., Abi Khalil, R., Tanganelli, E., Rai, N., Roffredi, L., Meybeck, A., Umulisa, V., Wolf, J. and Bernoux, M.** 2021. *2021 (Interim) Global update report – Agriculture, Forestry and Fisheries in the nationally determined contributions*. Environment and Natural Resources Management Working Paper No. 91. Rome, FAO. https://doi.org/10.4060/cb7442en

To address the abovementioned challenges, since 2015, FAO and the United Nations Development Programme have partnered to work with countries to integrate adaptation solutions specifically for the agriculture sector as part of the broader NAPs developed by countries. The programme titled "Integrating Agriculture in National Adaptation Plans (NAP-Ag)" has worked with 11 countries, to identify and integrate climate adaptation measures for the agriculture sector into national planning and budgeting processes, in support of achieving the Sustainable Development Goals and the Paris Agreement. Two of the key avocado producing countries, Colombia and Kenya, are included in NAP-Ag programme. While the plans developed do not focus on the tropical fruit sector, they warrant further consideration given the identification of climate risk factors for agriculture in the plans, and the adaptation measures proposed, which are also relevant for tropical fruit production (e.g. water management, soil conservation, protection of biodiversity, agroforestry and early warning systems). Some examples of the support provided by the NAP-Ag programme to these countries are highlighted in Table 3.

Table 3. Summary of the support provided by the NAP-Ag Programme to countries for the development of their NAPs

Country	NAP-Ag Support
Colombia	Launched in 2017, NAP-Ag activities focus on strengthening the formulation process of the Climate Change Plan for the agriculture sector, that addresses adaptation and mitigation in a cohesive manner, as well as focusing on the implementation of adaptation solutions at the family farming level. Areas of support included: • Vulnerability and risk analysis. • Monitoring and evaluation. • Develop an integral management plan of climate change for the agriculture sectors. • National climate vulnerability assessment for the agriculture sectors. • Agroforestry cocoa pilot system adapted to climate change. • Platform for the exchange of adaptation experiences in the agriculture sector. • Integrating gender in national adaptation planning for agriculture sectors. • Climate finance.
Kenya	NAP-Ag activities in Kenya are oriented towards promoting and implementing climate-smart agricultural practices for the long term. Technical support was provided to develop the Kenya Climate Smart Strategy 2016–2026. Short- and medium-term contributions include: • Increasing awareness on climate change impacts and assessing climate risk and vulnerability of agricultural value chains. • Identifying synergies between adaptation and mitigation. • Promoting uptake of climate-related information for agriculture. • Developing and upscaling specific adaptation in the agricultural subsectors.

Source: Adapted from **FAO.** 2023. Integrating Agriculture in National Adaptation Plans. [Cited on 2 May 2023]. www.fao.org/in-action/naps/partner-countries

In recent years, work under the NAP-Ag programme has also progressed to include support for the design of monitoring and evaluation (M&E) systems for adaptation in the agriculture sectors to be incorporated into NAPs (FAO and UNDP, 2023). According to FAO and UNDP (2023), countries face several challenges in doing M&E of adaptation, including the long-time scales over which climate change impacts unfold; the uncertainty of climate impacts; context specificity and lack of common indicators; attribution of impact to adaptation and/or development interventions; and access to and availability of relevant climate data. However, progress is ongoing and there is recognition that it is essential to link M&E systems to broader adaptation planning and implementation processes, including NAPs and NDCs.

In the context of the tropical fruit industry, understanding how specific commodity sectors like avocado production and export can contribute towards the achievement of mitigation and adaptation targets set out in the NDCs and NAPs is useful. It may help the industry to align their efforts with those at a national and sub-regional level where they exist and demonstrate to policy makers that collective efforts are being made by industry to support these plans. Specific initiatives such as the monitoring of carbon and water footprints with open-source tools (such as the one currently under development by the Responsible Fruits Project for the pineapple industry) could help producer and exporter associations to demonstrate in a concrete way how adaptation and mitigation efforts are being supported in line with national strategies, plans and objectives. Similar approaches should be considered to monitor and evaluate adaptation practices identified in **Chapter 4** of the guide, so that industry-led/public–private partnership initiatives can be highlighted as contributing towards the delivery of national adaptation goals.

Chapter 3.

Climate risks facing avocado production

As discussed in **sub-section 2.2.1** of **Chapter 2**, for all avocado-producing countries identified in the guide, an increase in average temperatures is predicted by the end of the century, and more frequent and intense extreme weather is expected as a result. Temperature plays an important role in regulating plant growth and the fruit development cycle in avocado plants, including reproduction, fertilization, pollen viability and fruit setting. Thus, very high or low temperatures will affect the performance of the plants and overall production as explained below. Likewise, changes in temperature, especially warmer weather, could result in a significant shift in the potential areas suitable for tropical fruit production, already noted in some of the main avocado producing countries.

On the other hand, unlike temperature trends, future precipitation patterns do not show a clear tendency and vary depending on the region and producing country. Countries such as Colombia, Kenya and Peru are projected to experience an increase in rainfall by 2100, while for Mexico, Chile and South Africa, a reduction in precipitation is projected (see more details in **sub-section 2.2.2**). Based on these projected climate trends, this chapter presents a summary of climate risks identified through a review of the scientific literature and consultations held with producers and associations from the avocado industry. Understanding these risks can help avocado producers, associations and companies to consider future climate risks in decision-making processes to manage and mitigate potential impacts accordingly. Each risk:

- identifies and describes the effects of climate change on avocado production;
- illustrates other potential impacts that climate change and extreme weather events may have on social and economic dimensions of avocado production; and
- highlights the climate risks experienced in different avocado producing countries.

The main climate risks and some impacts on avocado production are summarized in **Table 4**.

Table 4. Main climate risks and other associated impacts and threats for avocado production

Climate variables	Risks and impacts identified	
Temperature	Increasing temperatures	Extreme heat
	Frost	Hailstorms
Precipitation	Intense rainfall	Water shortage
	Drought	Changes in rainfall patterns
Mixed and other	Alternate bearing cycle	Reduction of pollinators
	Spread of pests and diseases	Soil erosion
	Strong winds	

3.1 Temperature

High temperatures

Avocado trees require a temperature from 17 °C to 24 °C for normal development, where at a temperature of 20 °C the plant reaches its optimal growth. Likewise, the avocado tree requires a minimum temperature from 10 °C to 17 °C and a maximum from 28 °C to 33 °C for fruit set. Outside these thresholds, avocado production will be affected as summarised in **Table 5**, impacting the total output and income of avocado growers.

Table 5. Increased temperature impact on avocado production

Production stage	Impact
Flowering	Temperatures above 33 °C in humid subtropical climates and over 21 °C in high-altitude areas shorten the flower opening period and reduce the number of flowers that open, decreasing pollen viability and fruit production.
Fruit setting	Temperatures from 28 °C to 33 °C can cause the abortion of Hass embryos and, when combined with low humidity, cause small-size fruits (below 5 mm) to fall from the tree.
Quality	High temperatures and associated solar radiation affect the avocado skin and may enable the conditions for the proliferation of diseases. Depending on the degree of damage, sunburnt fruit might not meet quality requirements in international markets.

Sources: **Álvarez-Bravo, A., Salazar-García, S., Ruiz-Corral, J.A. & Medina-García, G.** 2017. Scenarios of how climate change will modify the 'Hass' avocado producing areas in Michoacán. *Revista Mexicana de Ciencias Agrícolas*, 8 (19): 4035-4048; and **Howden, M., Newett, S. & Deuter, P.** 2005. *Climate Change – Risks and Opportunities for the Avocado Industry*. New Zealand and Australia Avocado Grower's Conference. 20 to 22 September 2005. Tauranga, New Zealand. https://synergetictrees.org/climate-change-risks-and-opportunities-for-the-avocado-industry

High temperatures can cause heat stress significantly affecting plant development such as seed germination, vegetative growth, and plant reproduction. Heat stress may impair crucial physiological processes in the plant like photosynthesis and respiration rates, stomatal conductance, and leaf water potential homoeostasis. Net carbon assimilation may also decline due to increased photorespiration (Shapira *et al.*, 2021).

Pollen viability is also influenced by temperature. Maximum pollen adhesion to the stigma and optimal pollen germination occurs at temperatures ranging from 20 °C to 25 °C (Hormaza, 2014). Outside these thresholds (above 25 °C and below 15 °C), pollen germination and fertilization are inhibited.

High temperatures also negatively influence the fruit quality, where optimal ripening occurs between 21 °C and 27 °C. Temperatures above 30 °C cause irregular ripening and darkening of the avocado flesh (Arpaia *et al.*, 2018), whereas abnormal and over-ripening is observed at 40 °C or higher (Acosta *et al.*, 2022). This implies that when warm temperatures are experienced, the likelihood of fruit damage increases, with associated negative impacts on the total marketable product available.

Increased solar radiation

Warmer weather is expected to increase solar radiation. The enhanced radiation will likely lead to sunburn of leaves and fruits when direct, intense sunrays fall onto fruit without sufficient protective leaf cover. The tender tissues of branches exposed to direct solar radiation can also suffer burns, and damaged branches may eventually dry out and die. Sunburn damage on the avocado skin appears as a yellowish green blemish due to discoloration of the green pigment (chlorophyll) in the skin (Steyn, 2020; **Figure 8**). Severe sunburn damage reduces the marketability of the fruit as it lowers its quality for export. Increased radiation produced by warmer temperatures has also been associated with increased susceptibility to pathogens (Howden, Newett and Deuter, 2005).

Figure 8. Avocado with symptoms of sunburn

© *FAO/Astrid Randen.*

Lower temperatures

Low temperatures of approximately 7 °C to 10 °C and a short photoperiod are required to start flowering. Temperatures from 20 °C to 25 °C during the day and 10 °C at night are also required to ensure good fertilization and good fruit set (Ortega, 2022). However, exposure to extended periods of night temperatures at 10 °C or less during the flowering phase can reduce pollination, fruit set and fruit retention (Howden, Newett and Deuter, 2005). This occurs as low temperatures shorten the female flower phase reducing cross pollination, while flowers also become less receptive to pollen. Likewise, pollinators, such as honeybees, are less active under cold weather conditions. Poor fruit set can also cause the avocado tree to begin growing excessively, which may require pruning after harvesting to control growth. Reduced fertilization and fruit setting can result in a significant yield reduction and economic losses.

Cold stress also diminishes the rate and efficiency of photosynthesis, caused by a decrease in carbon dioxide diffusion from the atmosphere, as well as metabolic changes suffered by the plant when cold weather is experienced (Chung *et al*., 2022). The exposure to very low temperatures, even for a short time, can cause irreversible damage to the plants, as severe cold stress can break their photosystem and antioxidant system (Chung *et al*., 2022).

Hailstorms

Hail is a highly sporadic event, which makes it difficult to predict at an exact point in time for a certain geographical location. Using historical data of hailstorms, companies and institutions may be able to predict the prevalence of hail, the time of year when storms may occur and the average intensity of the event (Steyn, 2020). Nonetheless, climate change, through higher temperatures are also likely to make hailstorms more frequent and severe. Although the prediction is less exact than other weather events, warmer weather will enable factors contributing to more frequent hailstorms and the formation of larger hailstones (Raupach *et al*., 2021). This risk has been identified as one of the main concerns to the avocado sector, particularly in Chile, Mexico and South Africa, which has negatively impacted production. According to project participants, hailstorms have resulted in reduced productivity due to loss of flowers and fruit set, negatively impacted fruit quality (smaller size), and caused serious damages to trees and infrastructure.

Hailstorms can affect avocado production in different ways. Hail affects flower production, and when accompanied with increased wind events, hailstorms can result in a severe reduction of flower quantity on trees and reduced fruit set (Steyn, 2020). When flowers and fruits are already developed, hailstorms can cause a total loss of fruit crop and promote the proliferation of fungal pathogens (Vargas *et al*., 2012). Fruit quality is also impacted, either directly by damaging mature fruit (**Figure 9**) making them unmarketable or injuring immature fruits from rubbing on nearby branches or on other fruit (Steyn, 2020). To put this in perspective, a study conducted in Mexico showed that heavy hailstorms in 2010 damaged more than 10 000 ha of avocado orchards in Michoacán and led to the total loss of production and in some cases, the full defoliation of trees (Vargas *et al*., 2012).

Figure 9. Effect of hail on the avocado fruit

Source: **Steyn, T.C.** 2020. *Comparing hail risk management strategies through whole-farm multi-period stochastic budgeting for avocado production in South Africa.*

3.2 Precipitation

Water is critical for avocado production. Water requirements for avocado vary with weather conditions (rainfall and temperature), soil types, tree age and crop load. Water deficit or excess can negatively affect avocado production at various stages (**Table 6**).

Table 6. Summary of impacts of water deficit or excess on avocado production

Production stage	Impact
Flowering	Insufficient rainfall without supplementary irrigation leads to the loss of flowers, reducing fruit production. Excessive rainfall during the flowering period impairs pollinator action and pollen quality, affecting fruiting.
Fruit setting	Very low humidity can lead to the desiccation of flowers and failure of fruit setting.
Quality	High humidity can lead to fruit spotting reducing quality. Low rainfall, combined with high temperatures can affect the size of avocado fruits.
Plant establishment and development	High humidity also brings the proliferation of pests and diseases, such as *Phytophthora cinnamomi* and *Monolepta* sp. The prevalence of pathogens can be exacerbated with increased temperatures and if soils present degradation characteristics.
Production expansion	Low precipitation and insufficient underground water can limit both the establishment of new orchards and maintaining production continuity. Conversely, intense rains and winds may produce fruit loss, tree and infrastructure damage.

Source: see the list of references in the end matter.

Drought and water deficit

Low water availability negatively affects avocado production resulting in plant stress and increased risk of soil erosion. Water deficit in trees shrinks the trunk diameter and decreases stomatal conductance, stem water potential, net photosynthesis and net carbon assimilation (Priego and Rodriguez, 1994). It also decreases the potential productivity and leads to fruit development disorders (Mesa *et al.*, 2021). During fruit pre-harvest stages, water deficit forces the avocado tree to redistribute water to other parts of the plant, increasing the fruit dry matter, delaying the ripening process and reducing the overall quality of the fruit (Mesa *et al.*, 2021).

Lack of water during flowering, when the evapotranspiration surface of the tree increases substantially, can decrease fruit set and increase fruit fall in the first stages of development. During the fruit development and growth phases, the lack of water can result in smaller-sized fruits and alterations in the internal quality (Ortega, 2022).

On the economic side, water scarcity also deepens the vulnerability of avocado farms, particularly of small-scale farms, as water becomes more expensive and preference in water allocation is often given to large agribusiness (Sommaruga and Eldridge, 2020). In some producing countries in Latin America, producers are already experiencing growing water competition with other industries and domestic use, particularly during the dry season (European Commission, 2021). Such competition has also created conflicts and tensions between producers and local communities according to some avocado companies and associations participating in the project.

Flooding and increased precipitation

Flooding is a complex stress which can be caused by natural floods, high rainfall, over-irrigation, or perched water tables (Kourgialas and Dokou, 2021). It comprises several individual stresses, including hypoxia, changes in soil pH, and increased pathogen activity, all of which contribute to the overall stress experienced by the plant.

Avocado trees have a relatively shallow root system that does not spread much beyond the tree canopy. Roots have few root hairs, poor water uptake and sensitivity to low soil oxygen concentrations. These characteristics make avocado one of the most susceptible fruit trees to soil flooding. Flooding produces hypoxic or anoxic conditions in the root zone by displacing oxygen in the soil, and even a few days of standing water in the root zone can negatively impact physiological processes (Sanclamente *et al*., 2014). Impacts include reduced photosynthesis, stomatal closure and decline in root hydraulic conductivity, causing a reduction in growth and yield (Reeksting *et al*., 2016). Hypoxia can ultimately lead to tree mortality as aerobic respiration is reduced and uptake of nutrients is inhibited (Kourgialas and Dokou, 2021).

3.3 Alternate bearing cycle

Avocado trees are prone to suffer from the alterative bearing phenomenon, which can be stimulated by different factors including extreme weather events such as frosts, low or high temperatures. Alternate bearing refers to an on-crop/off-crop cycle across two years that results in a large crop of small avocados in one year, followed by small crop of large avocados the next year. Once started, an alternate bearing cycle can be difficult to stop as a large production of flowers and fruits in one year causes the exhaustion of the tree, inhibiting fruit set and flowering, and a smaller production next year. Likewise, a small off-crop leads to robust fruit set and flowering and a large crop the following year (Paz-Vega, 1997).

Alternate bearing has a severe negative impact on the commercial avocado industry as production and sales are affected. The on-crop stage is characterized by a large number of small-sized avocados, which have reduced commercial value at harvest, and which depending on the size, makes them largely inadequate for export. On the other hand, the off-crop stage produces larger fruit size but in a small quantity, which may limit growers' capacity to obtain sufficient income for the season (Lovat, 2010).

Poor crop management practices can also trigger alternate bearing in avocado in addition to climate factors. For instance, inadequate watering during bloom or fruit set can lead to the production of a low or excessive number of flowers and/or fruit drop. Poor nutrient management, such as low fertilization, can also stimulate excessive flower/fruit drop. Inadequate pruning can promote the generation of excessive foliage with less fruit setting (Lovat, 2010). Inefficient pollination activity and systems may also affect fruit setting and enable alternate bearing (Thorp, 2011).

Sudden changes in market trends can also influence alternate bearing if producers allow fruit to hang on the trees for too long before harvesting in order to obtain a higher average unit price. This practice may inadvertently stimulate the alternative bearing phenomenon for the following season, resulting in economic losses.

3.4 Pests and diseases

Climate change is expected to exacerbate the frequency and resistance of pests and diseases (Skendžić *et al.*, 2021). Changes in temperature and humidity will shorten pest cycles, increasing damage to orchards. In some regions, the incidence of diseases may increase due to increased precipitation and higher humidity levels in orchards.

Some of the main pests and diseases in avocado production that are likely to become more prevalent are listed in **Table 7**.

Table 7. Prevalent pests and diseases present in avocado production

Pest or disease	Countries where pests have been observed
Phytophthora cinnamomi	Chile, Colombia, Mexico, Peru, Kenya, Australia, New Zealand, Israel, Spain, Morocco, United States of America, South Africa, the Dominican Republic
Raffaelea lauricola	United States of America, Southeast Asia.
Colletotrichum gloeosporioides	Chile, Colombia, Mexico, Peru, Kenya, South Africa
Thrips (*Heliothrips haemorrhoidalis*)	Chile, Colombia, Mexico, New Zealand, United States of America, Kenya, South Africa, Israel
Verticillium dahliae	Colombia, Chile, Ecuador, Mexico, South Africa, Israel, Spain, Australia, Italy
***Erwinia* spp.**	Chile, Colombia, Mexico, Peru, Guatemala, Spain
***Dothiorella* stem canker (*Botryosphaeria* spp.)**	Chile, United States of America, Mexico, Spain, Chile, South Africa, Peru
***Cercospora* spot**	Mexico, South Africa, Peru, Colombia, Central America
Avocado sunblotch viroid (ASBV)	Peru, South Africa, Spain, Australia, Israel, United States of America

Pest or disease	Countries where pests have been observed
Avocado leaf gall (*Trioza anceps* Tuthill)	Mexico, Central America, Peru
Avocado stem weevil/avocado branch borer (*Copturus aguacatae* Kissinger)	Mexico, Guatemala
Small avocado seed weevil (*Conotrachelus aguacatae* Barber)	Mexico, Nicaragua
Avocado seed weevil (*Heilipus lauri* Boheman)	Mexico, Central America, Colombia
Avocado seed moth (*Stenoma catenifer* Walsingham)	Mexico, Central America, Argentina, Brazil, Colombia, Ecuador, Guyana, Peru, Venezuela

3.5 Reduction of pollinators

Changes in climate will have detrimental effects on avocado pollinator populations and systems (**Figure 10**). Warmer temperatures can stimulate early blooming reducing the food availability from plants to pollinators, especially to those who cannot adapt. Longer dry seasons and droughts can also lead to a lower production of nectar by flowers in order to preserve energy, which implies lower sugar and calories available to pollinators, affecting their health and reproduction.

Extreme rainfall can also present a challenge to pollinators, as it may reduce the number of hours pollinators can fly to gather floral resources. Honeybees, one of the main pollinators of avocado, are particularly sensitive to wind, rain and low temperatures (Dymond *et al.*, 2021). Together, these factors would result in lower pollination efficiency, less fruit set, lower yield and marketable potential for the industry (Acosta, 2022).

Pollinators play a crucial role in avocado production as they directly affect fertilization and fruit setting. A study conducted in Kenya showed that a significantly lower fruit set was observed for self- and wind-pollinated (17.4 percent) or self-pollinated flowers (6.4 percent) in comparison with insect-pollinated flowers (89.5 percent) (Sagwe, 2021).

3.6 Soil erosion

Soil erosion is the process of wearing away or severely damaging the top layer of the soil (Montenegro *et al.*, 2020). Erosion can be caused by wind, water currents from streams, heavy rainfall and irrigation, temperature changes or the inadequate use of the resource (e.g. poor implementation of soil management practices, overuse of agrochemicals). Other causes that contribute to soil erosion and degradation are deforestation and land use change, as well as overgrazing (Leon *et al.*, 2012).

Figure 10. A honeybee *A. mellifera* in an avocado flower

Source: **Sagwe, R.N., Eters, M.K., Dubois, T., Steffan-Dewenter, I. & Lattorff, H.** 2022. Pollinator efficiency of avocado (*Persea americana*) flower insect visitors. *Ecological Solutions and Evidence*, 3(4). https://doi.org/10.1002/2688-8319.12178

Climate change is likely to exacerbate issues linked to soil health, facilitating soil erosion processes. As discussed, rainfall is expected to increase in some of the main producing avocado countries, such as Colombia, Kenya and Peru, which increases the risk of soil erosion through the potential for higher topsoil runoff. This is particularly concerning in production areas with steep slopes and with bare soils. The erosion may in turn increase the frequency of waterlogging produced by intense rainfall, creating the conditions for the proliferation of *Phytophthora cinnamomi*, particularly in places where the fungus is already problematic (Howden, Newett and Deuter, 2005). Warmer weather may result in higher soil temperatures and evaporation, affecting moisture and overall structure of the soil. This may lead to increased water demand for irrigation and the risks to avocado supply reliability (*ibid.*).

Cultivation of fruit trees on downward ridges can also increase the vulnerability of soil to erosion. The soil movement necessary for ridge construction is an erosion process itself, as it provokes a significant movement and alteration of the cropping soil layer. In turn, the bare and degraded soil is more prone to suffer from water and wind erosion (Youlton *et al*., 2010).

Soil erosion can be reflected in different degradation processes, including soil pollution, fertility decline and salinization. Soil degradation issues have been observed in avocado producing areas in Chile, Kenya, Mexico and Peru. Erosion and degradation affect the capacity of the soil to retain and drain water. As discussed in the section on precipitation, avocado requires good drainage in the soil to be able to thrive and prevent the incidence of fungal pathogens, since avocado is one of the most sensitive species to radical asphyxia.

Overall, soil and land degradation have negative impacts on production, by not only lowering productivity but also negatively affecting ecosystems and biodiversity adjacent to agricultural production areas (European Commission, 2021).

3.7 Strong winds

Avocado is susceptible to strong winds, both dry and cold, which can inhibit pollination and fruiting. Strong winds can also cause the fall of branches, flowers and fruits, and impact the quality of fruit on trees through injuries on fruit skin due to friction between fruits and branches (**Figure 11**).

Hot dry winds are already having detrimental effects on avocado production in producing regions in South Africa, Israel and California, and are expected to become more prevalent with higher temperatures and heat waves expected under climate change conditions (Rodríguez Pleguezuelo *et al*., 2018; Ish-Am, 2005). Hot dry winds can hinder the flight and health of pollinating agents, which reduces the number of pollinated flowers and therefore fruits (Lazare *et al*., 2022). Humid winds, particularly in areas where avocado production is exposed to hurricanes, can also have negative impacts on the avocado's root system, and overall production if the cultivated land does not have good natural or added protection against the wind (FHIA, 2008). Humid winds can cause severe damage to trees by breaking of branches and falling fruit, especially when fruit is small.

Figure 11. Signs of wind damage on avocado skin

Source: **New Zealand Herald.** 2022. Bay of Plenty avocado, kiwifruit growers counting cost of Cyclone Dovi's winds. Cited 12 June 2023. www.nzherald.co.nz/the-country/news/bay-of-plenty-avocado-kiwifruit-growers-counting-cost-of-cyclone-dovis-winds/D3XGLBWR7ZEQ32LOTQVJJA543U/

Chapter 4.

Climate change adaptation strategies for avocado

Following on from Chapter 3 and the discussion on climate risks and impacts on avocado production, this chapter presents 15 adaptation practices identified through consultations with key informants from the industry and in the scientific literature. The practices recommended are closely linked to different approaches that promote both climate adaptation and sustainability across multiple dimensions. These include climate-smart agriculture, agroecology, regenerative agriculture and precision agriculture.

The selected practices can help avocado producers adapt to the main climate risks identified, with direct contributions to resilience building to future climate shocks. Each practice:

- identifies which climate risks can be minimized, or in some cases prevented through the adoption of the practice;
- gives a brief description of the practice and how it is implemented;
- illustrates other potential co-benefits on environmental, economic or social dimensions; and
- highlights an example of implementation in practice by a producer association or company where available.

Table 8 summarizes the practices included in this chapter and provides an overview of the climate hazards and associated impacts they address. As seen in the table, implementing one adaptation practice may help to address multiple risks, and several practices combined may strengthen the overall resilience of the production system.

The examples included in this chapter highlight innovative approaches that avocado growers, companies and associations are taking to adapt to climate change. These practices are for illustration purposes only. They have not been validated in the field by FAO nor officially endorsed.

Table 8. List of climate adaptation practices and climate hazards and impacts they address

Climate hazards and impacts / Adaptation practices	Intense rainfall	Changes in rainfall patterns	Extreme heat	Frost and low temperatures	Strong winds	Hailstorms	Increasing temperatures	Water shortage	Drought	Soil erosion	Solar radiation	Spread of pests	Reduction of pollinators	Alternate bearing
Agroforestry	X		X	X	X				X	X	X	X	X	X
Anti-frost systems				X										X
Drainages systems	X	X								X				X
Early warning systems	X	X	X	X		X	X	X	X	X		X		X
Integrated pest management							X			X	X	X	X	
Integrated water management	X	X	X		X			X	X	X		X		X
Mulching and cover crops	X	X	X	X	X	X			X	X	X	X	X	X
Organic fertilizers (composting, biofertilizers)	X	X						X	X	X			X	X
Plant breeding	X	X	X	X	X	X	X	X	X	X	X	X		
Protection of pollinators and beekeeping							X	X	X	X		X	X	
Shade nets			X	X	X	X					X			X
Sustainable forest management	X	X	X	X	X		X		X	X		X	X	X
Waste management										X		X		
Water-efficient irrigation systems		X	X	X				X	X	X				X
Windbreaks or living fences			X	X	X	X			X	X		X	X	X

Note: You can click on the different practices for more details.

4.1 Agroforestry

Climate risks and impacts addressed: strong wind, extreme heat, intense rainfall, soil erosion and landslides. The microclimate generated by the presence of trees and vegetative cover can also help to minimize the effects of **droughts** and **frost**. These systems can also contribute to **pest control, protect pollinators** and help to manage **alternate bearing cycles**. Co-benefits include diversifying production which can generate an additional income source for producers in case of reduced quality and yield of avocado production. Agroforestry can reduce the use of external inputs, such as fertilizers and pesticides.

The practice:

Agroforestry is a technique of combining flora[10] species with the predominant production system, in this case, avocado production. Agroforestry systems are designed to create common benefits from the interaction among the different the species, without creating competition. The association optimizes biodiversity and other factors, including ecosystem services (nutrient and water cycling), improves soil quality and nutrient availability, and enhances pests and diseases management (Lugo, 2018). The implementation of agroforestry systems is recommended on degraded areas that are suitable for farming and/or forestry in order to recover forest areas without the need to sacrifice avocado production.

Ecosystem benefits of agroforestry also include disaster risk reduction. The presence of trees and shrubs promotes soil anchoring/stabilization and reduces landslides following strong storms, leading to lower damages and losses in infrastructure and crops. This also results in savings associated with expensive infrastructure solutions, such as of drainage ditches, storm sewers or slope stabilization structures (Schick *et al.*, 2018). Studies have shown that planting trees and shrubs between crops and around land plots can help prevent soil erosion, restore soil fertility and provide shade to crops. Higher biomass density through perennials also has the potential to absorb more carbon than seasonal crops only, thereby offsetting and mitigating some of the effects of climate change (Oloo *et al.*, 2013).

Avocado plantations incorporating agroforestry practices can be more productive and more economically profitable than monoculture systems. A cost-benefit analysis conducted in Mexico showed higher benefit-cost ratio in the agroforestry system (avocado–guava–coffee) compared to the monocropping plantations (Montiel-Aguirre *et al.*, 2008). In Ethiopia, Honduras and Southern California, intercropping avocado with shade-grown coffee has also displayed good performance in terms of productivity and profitability (Biazin *et al.*, 2016; Seed Change, 2018; Montiel-Aguirre *et al.*, 2008).

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[10] Small ruminants or poultry can also be integrated in the systems, but the introduction of livestock is not discussed in this document due to the nature of the production systems analysed.

However, it is important to highlight that the ecological productivity of agroforestry systems is closely related to how the system is designed, that is, the types of plant species integrated in avocado plantations and the plant density in the orchard. Likewise, considerations are needed in plant selection as canopy levels, shade tolerance, nutrient and water requirements vary among avocado and other plants, with potential impacts on avocado plant development and yield at different stages. In tropical areas, high-value species such as nopal (*Opuntia ficus-indica*), blackberry (*Rubus fruticosus*), macadamia (*Macadamia integrifolia*) and cardamom (*Elettaria cardamomum*) can be considered for agroforestry systems if these are well adapted to agro-climate conditions (Montiel-Aguirre *et al*., 2008). In sub-tropical and Mediterranean climates, Millettia ferruginea (*Fabaceae*), Cordia Africana or Sudan teak (*Boraginaceae*), and species of the Ficus genus could be combined with avocado production (Biazin *et al*., 2016).

Box 1 highlights an example of agroforestry practices from Viet Nam where coffee, macadamia and pepper have been integrated into the predominant avocado production system.

Box 1. Introducing agroforestry systems in avocado production areas in Viet Nam

Company or association: Anonymous
Region: Viet Nam

The cooperative started as a family business in 1991 and since then it has expanded to serve the national and regional markets. The main production area for the cooperative is in the northern part of the country where forests and suitable agro-climatic conditions for the cultivation of high-value crops prevail.

The cooperative has associated avocado (West Indian variety) with other crops such as macadamia, coffee and pepper to promote more sustainable production systems among the cooperative members. The diversification of agricultural production has reportedly allowed small-scale producers to have more stable incomes throughout the year, by offering a wider variety of products to the markets. The latter has been particularly important for Viet Namese producers as the projected avocado price in the country is expected to decrease in the coming five years, according to a market study conducted by the cooperative.

Careful deliberation is needed in the selection plants to be incorporated in agroforestry systems. As in the case of **windbreaks and living fences**, non-native species used in agroforestry can become invasive if their natural enemies are not present in the environment in which they are incorporated. For example, *Opuntia ficus-indica* is a profitable crop in Mexico, but it can become an invasive species in avocado producing regions such as Kenya and Australia. Likewise, *Rubus fruticosus* can be very aggressive in non-native avocado-producing regions such as South Africa, New Zealand and Australia, and even displace native vegetation (CABI, 2019). Thus, it is very important to select complementary species that do not compete with avocado trees and local biodiversity.

On the economic side, considerations should be given to the costs related to the cultivation of other commercial and/or non-commercial crops (e.g. labour, machinery, equipment, seeds, inputs), as well as the potential supplementary income generated by these, in order to determine the economic viability of the system.

4.2 Anti-frost systems

Climate impacts addressed: frost. Other benefits are the reduction of production losses during frost events.

The practice:

Anti-frost systems are practices and technologies that can allow producers to prevent, protect and mitigate the effects of frost on avocado trees and fruits. The practices and technologies vary widely in terms of timing, complexity and cost.

When planning an orchard, the selection of the location and the design of the orchard rows can be simple options to reduce the severity of frost events. The selected production area would ideally have no frost history. If this is impossible due to other agroclimatic, soil and socioeconomic conditions, producers should ensure that the production location has some slope and avoid planting in the low points to prevent the impact of strong cold wind currents.

It is important to consider that in avoiding frost events, producers might be motivated to plant in deep slope areas, such as mountainous areas. However, this may have negative ecological consequences including land use change, land degradation, increased disaster risk (landslides), and depletion of water resources for production and local communities.

Another simple preventive option, particularly for young trees, is the use of **frost covers**. The covers must cover all sides of the trees, including the canopy, to help prevent total tree exposure (Government of Western Australia, 2017). The covers can also reduce the loss of heat by the plant due to inverse radiation.

Irrigation systems can serve as antifreeze measures. Overhead (above crown) sprinklers that continuously spray water on the tree can help the canopy release heat as the water turns to ice, avoiding damages from frosting. This method is more effective on mature trees than on young trees or seedlings (Remy *et al.*, 2019). However, irrigation can be expensive due to the cost of water and fuel for water pumping or channelling in the production area. Likewise, this measure can potentially be environmentally unsustainable if irrigation is needed to address long frosting periods (e.g. seven-hour freeze), which would require large supplies of water for constant spraying (Remy *et al.*, 2019).

Irrigating before the expected frost can also prevent harsh damage on trees, as wetted and moist soils will absorb and release more heat than dry soils (Government of Western Australia, 2017).

The application of **frost protective solutions** is another potentially helpful practice in avocado orchards. These are applied via sprinklers and have been tested in fruits such as grapes and sweet cherry. The application of cellulose nanocrystals improved the cold hardiness of reproductive buds of the two fruits by 2 °C to 4 °C (Alhamid *et al*., 2018). Further research would be needed in avocado orchards to test the efficacy and safety in avocado production and trade.

Ventilation systems consist of industrial (horizontal or vertical) fans that mix the cold air within the canopy with warmer air from the upper level, taking advantage from the thermal inversion that takes place during cold nights (Bar-Noy *et al*., 2019). Thus, the ventilation does not create warm air, but rather redistributes the heat already present in the air. The horizontal wind machine draws warmer air from the upper level and re-directs it to the ground level towards the plants, whereas the vertical wind machine takes the cold air from ground level and pushes it above. A study conducted in Israel showed that horizontal machines could increase temperatures by around 2.4 °C and 1.82 °C at 20 and 125 meters from trees, respectively. Although these systems provide some degree of frost protection, they require very careful orientation of the wind and distance from trees to avoid risks associated with the fall of inflorescence buds and flowers (Bar-Noy *et al*., 2019). **Box 2** highlights the use of these and other systems in Chile and the challenges faced to reduce the impact of frost.

Box 2. Use of anti-frost systems in Chile

Company or association: Anonymous
Region: Chile

Throughout the years, frosts have been a recurrent threat to avocado production in Chile, but in recent years these events have been increasingly difficult to predict in many regions, including the sixth region, one of the main producing areas. The unpredictability of the risks has made producers less able to prepare for this type of threat.

To respond to these challenges, the avocado production company acknowledged the use of methods against frosts such as cold and hot ventilation, adding hot water. These systems have allowed some level of control against the frosts that can be forecasted. Nonetheless, it was also noted that having permanent methods or technologies, especially to address unexpected frosts, would result in very high costs for producers.

Thus, further research on more affordable technologies or practices are needed to both help forecast and receive timely warnings about “off-season” frosts, but also to allow producers to be prepared when unexpected frost events occur.

The use of avocado varieties that are **resistant to frost** can also provide additional protection to producers. Despite the need for more research for the creation of varieties better adapted to below-zero temperatures (see section on **plant breeding**), some avocado species – including hybrids – exhibit characteristics that make them more resistant to low temperatures and frosts. Some of these are outlined in **Table 9** (University of California, 2023). It is important to note that the duration of below-zero temperatures will also play a determining factor on the degree of injury caused to the crop.

Table 9. Avocado varieties most resistant to cold stress and frost

Variety	Typical varieties	Critical temperature below which fruit and/or trees are subject to damage	Critical temperature above which fruit and/or trees are subject to damage
Mexican	Duke, Topa topa, Mexicola, Zutano, Bacon	-3.8 ˚C/25 ˚F	38 ˚C/100˚F
Hybrids	Fuerte, Puebla	-2 ˚C/28 ˚F	29 ˚C/84˚F
Guatemalan (Tender)	Ryan, Hass, MacArthur, Nabal, Endranol, Rincon	-1.6 ˚C/29 ˚F	33˚C/91˚F
Guatemalan (Very Tender)	Anaheim, Dickinson, Carlsbad, Challenge, Hellen	-1.1 ˚C/30 ˚F	34˚C/94 ˚F

Source: Adapted from **University of California.** 2023. Avocado Handbook. Cited 13 February 2023.

4.3 Drainage systems

Climate risks addressed: prevents damage to avocado plants and roots from **heavy rainfall and flooding**. Other benefits include the reduction of erosion. The systems can also help producers prevent **alternate bearing cycles** by managing humidity levels. Together, these could lead to higher quantities of premium quality fruit[11] with export potential. Better drainage can also **lower the incidence of pathogens**, in particular fungal pathogens that attack avocado roots such as *Phytophthora cinnamomi*. This can result in a reduced need for fungicides, lowering production costs and improving environmental outcomes. Some surface methods can also promote infiltration and groundwater recharge, reducing **water deficit** issues.

The practice:

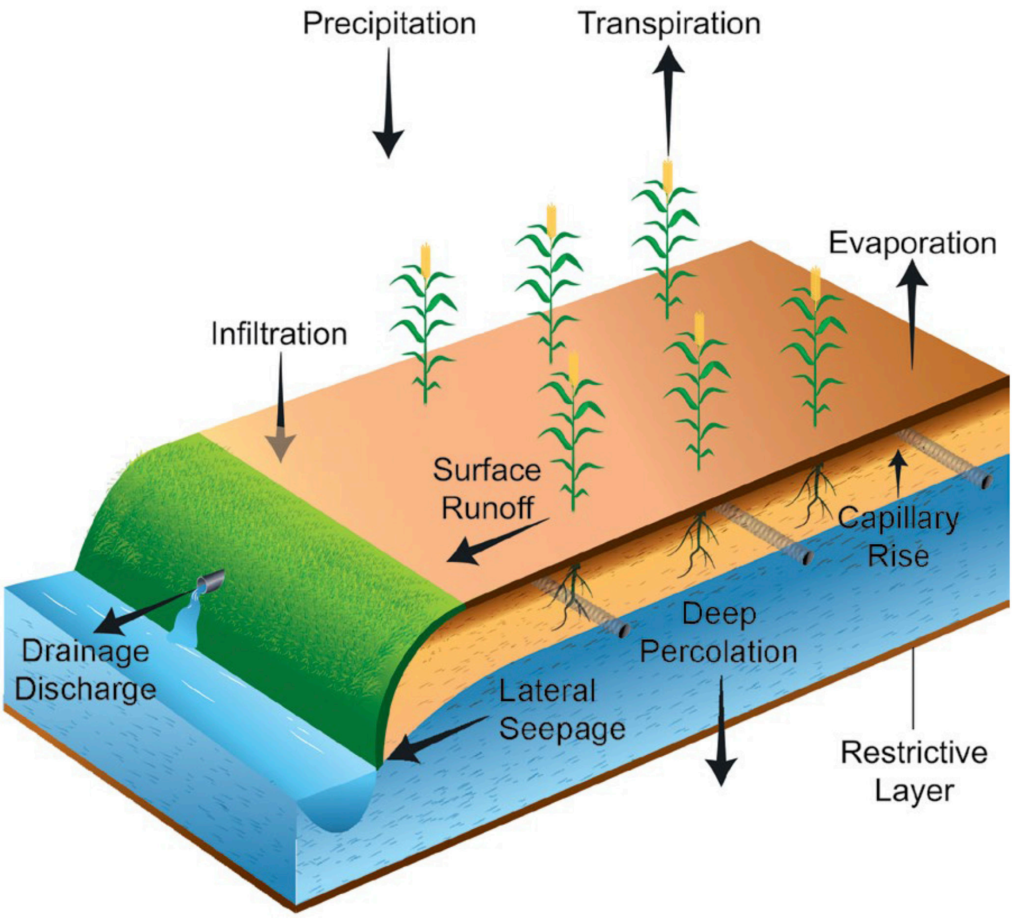
Water drainage in agriculture is carried out by systems that intercept and channel the excess water caused by intense rainfall, and disposes it in a safe location (e.g. reservoir, pond, water treatment

[11] Premium grade refers to the highest quality that can be achieved. Usually fruit quality is categorized as: Premium Grade, Grade 1 and Grade 2.

station). The water is transported rapidly through surface or sub-surface canals using gravity and in a manner that prevents soil erosion.

Surface drainage diverts excess water from the soil surface directly to streams, reducing the amount of water that will move into and possibly through the soil. Contour trenches and contour bunds are examples of simple techniques to that could act as surface drainage to help control surface runoff, diverge and distribute water at a speed that does not cause soil erosion. Surface draining measures can also promote water infiltration into the soil. On the other hand, **sub-surface drainage** uses ditches and drainpipes to collect water and divert it to streams. These systems might be more suitable in soils that are saturated (Fausey, 2005), as seen in **Figure 12**.

Figure 12. The water cycle on a field with sub-surface drainage



Source : **Ghane, E.** 2018. *Agricultural Drainage*. Michigan State University.

Mole drains are an example of sub-surface drainage, which can be used as a short-term and low-cost means to remove the excess water from the field. These are composed of unlined channels in the subsoil that act like pipe drains. The major advantage of mole drains is the low implementation costs compared to other sub-surface systems. Regarding durability, mole drains can last up to five years or more depending on the suitability of the soil (Ghane, 2018).

Surface and sub-surface systems can be combined in the same field and should be implemented on land where runoff can be safely disposed of (i.e. not on flat land), without causing soil erosion and/or contamination of water resources. Water table management is best suited to flat lands and can be achieved by a simple modification to the outlet of subsurface drainage systems. Maintaining a high-water table means that there is little room in the soil structure to store more water due to excessive rainfall. In fact, if the water table is being held at the optimum depth, any additional water would be unwelcome (Lang *et al*., 2023).

The size of the drainage system will depend on the depth of the water table (i.e. upper surface of the water-filled area in the soil, or "zone of saturation") and the maximum volume of water to be removed. The design of the drainage system requires knowing the physical properties of the soil (texture, gravimetric moisture, infiltration, apparent density, among others), and the orientation of the avocado trees and slope (Polón *et al*., 2011). This will allow tailoring the system based on the specific needs of the terrain. **Box 3** highlights how an avocado company in Colombia has implemented a combination of surface draining measures and underground drainage to manage the impacts of heavy rainfall associated with the La Niña phenomenon.

Box 3. Example of the use of irrigation systems in Colombia

Company or association: Cartama
Region: Colombia

Avocado production areas in Colombia have been affected by increased rainfall, accompanied by climatic events such as La Niña. To address the water excess brought by these events and prevent orchards from flooding and waterlogging, Cartama began modifying planting designs of the avocado orchards. The company has increased the distance between avocado trees and has developed contour lines to reduce water runoff in the plantations. Additionally, Cartama has established deep drainage with a pumping system to move water out of the production area to reduce excess water generated by heavy rainfall.

The company reports a positive impact on the protection of soil health, through the reduction of topsoil erosion and runoff by intense rains. The measures taken have contributed to avoiding landslides in the productive zones, thus also protecting the avocado trees and infrastructure.

It is important to consider that both surface and sub-surface systems drainage systems require maintenance and constant monitoring to ensure their correct functioning. This is necessary also to mitigate any potential negative effects on production and ecosystems. For instance, inadequate disposal of excess water can pollute freshwater streams through fertilizer runoff, transporting nitrogen to surface waters downstream and potentially promoting phosphorus loss from the soil (Mendes, 2021). In addition, failing to control the speed of water disposal could potentially promote the erosion of topsoil. Highly eroded soils may not be suitable for implementing surface drainage methods, as they can exacerbate these trends.

When designing drainage systems for avocado orchards, it is advisable to start with simpler surface measures (e.g. such as contour trenches and keyline ploughing) and complement them with the smallest number of drainage channels possible. Implementing underground drainage systems involves higher investment costs from companies than surface methods, and the presence of drainage channels cross-cutting plots can challenge the use of machinery and access to the farmland (UN Environment, 2015).

4.4 Early warning systems and monitoring systems

Climate risks addressed: early warning systems can be used to forecast any kind of climate or other biotic risks, such as pests.

The practice:

Early warning systems (EWS) are a key measure for climate change adaptation. EWS use integrated communication systems that can help producers prepare for expected or unexpected events in a timely manner. EWS can be used for events related to climate or non-climate events, such as pest and disease outbreaks. A successful EWS will allow producers time to protect their production from potential losses, reduce damages in land and infrastructure, and in some instances, save lives. EWS support the long-term sustainability and resilience of the production system.

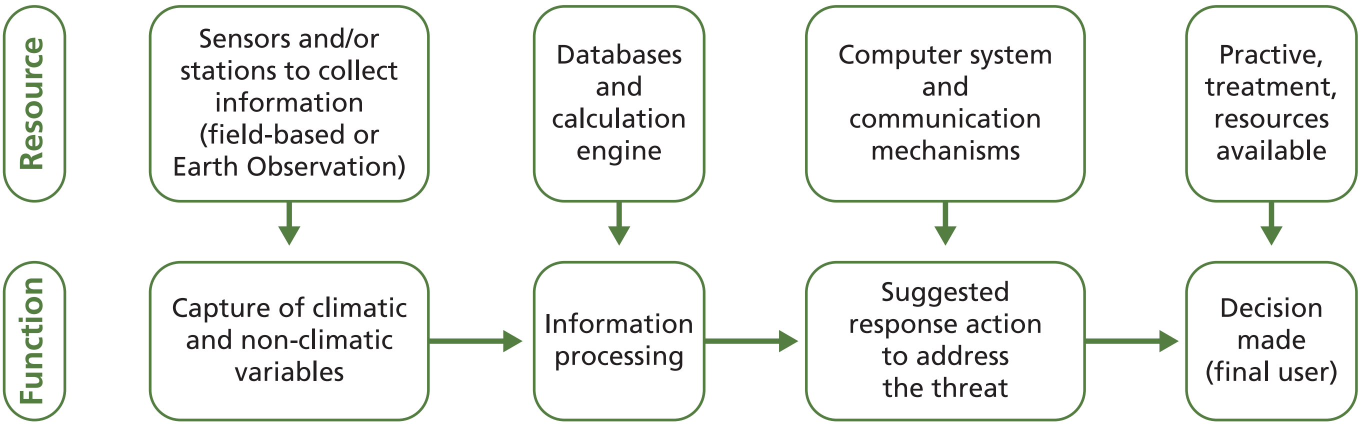
To be effective and complete, EWS need to include four key elements (UNDRR and WMO, 2022):

- **Knowledge about the risks that the avocado systems face.** This is based on the systematic collection of climate information (e.g. precipitation, temperature and relative humidity, soil conditions) and the assessment of risks in the production system and in nearby areas that are relevant for prediction of frost, drought, intense rainfall, among others. Information on the behaviour of the markets can and should also be monitored in companies focused on national and international sales. This information may include input prices, export prices, exchange rates, among others.

- **Detection, monitoring, analysis and forecasting of hazards** and the potential impacts of these on the production system (crop damage, infrastructure), including other socioeconomic factors (e.g. revenue losses, health hazards).
- **Effective dissemination and communication of the warning** in a timely, accurate and actionable manner. The warning needs to be accompanied with information about the likelihood of the event materializing and the impact.
- **Building response capacity** of producers and other stakeholders to respond to the warning.

EWS can obtain data from different sources, including meteorological stations at the field level, earth observation through geospatial information or traditional forecast methods available in different regions (see **Figure 13**).

Figure 13. Information flow in an early warning system



Source: Adapted from **Pérez Galarce, F.** 2016. Sistemas de alerta temprana para el control de alternaria en tomate. *Villa Alegre*, 338.

Evidence remains limited on the use of EWS in avocado production. However, studies on other crops have shown the potential benefits of using early detection and warning of climate and non-climate hazards. In Colombia, a study was conducted to detect how the early warning systems could be used to identify the risk of avocado wilt complex. A state-of-the-art platform was developed to collect daily data on precipitation, temperature and relative humidity in the environment, as well as the humidity and temperature of the soil. The information gathered was used to predict the likely incidence of wilt based on these variables and produce a warning message for producers and technical advisors via mobile phones. The warning is not only intended To prevent damage from the disease, but also to improve real-time monitoring and the design of plantations. The results indicated that the system was able to assess over 70 percent of the temporal factors causing the disease, which allowed producers to take preventive measures (Ramírez Gil, Giraldo Martínez and Morales Osorio, 2018). However, efforts are still needed to improve the accuracy of the predictions to help producers prevent and prepare for future risks and minimize losses in production and revenues.

In another example of EWS use, a project in Zimbabwe provided early warning and weather forecast messages to farmers twice a week to coincide with the Meteorological Services Department's 3-day forecasting period (FAO, 2022). The messages were delivered through radio or text messages (SMS), providing information on the weather conditions for the following three days. When extreme weather events were forecasted, special messages were broadcasted to allow producers to take anticipatory actions. The results showed that the EWS helped farmers to make important agricultural decisions such as postponing fertilizer application when they received notification that high temperatures and no rain were expected for the following days. Other producers were able to speed up the harvesting of their crops to avoid moisture damage after receiving a warning of upcoming rains.

A study in Niger showed that 82 percent of farmers receiving climate or weather information aided them to deploy actions to mitigate potential disasters in wheat production caused by droughts. The information received also enabled 64 percent of farmers to adjust their investments according to the profile of the upcoming rainfall season. The use of climate information and related advice led to an increase of about 10 bags of 100 kg in annual millet production per farmer, representing an income increase of about 73 000 CFA (or 118 USD)[12] from an average farmland of 3 ha. At the community level, early warning also had important socioeconomic impacts as it allowed for better management of seeds and inputs, and planning for seasonal migration (Seydou *et al*., 2023). This might have particularly important implications in avocado producing areas that depend on domestic or international migrant labour for the production and harvesting of avocado.

Early detection of potential adverse effects of biotic and abiotic stresses can also be done through relatively simple methods. A study in Japan showed that growing few crops or plants that are particularly sensitive to the given risk, in this case calcium deficiency (tip burn) in lettuce, could act as an early warning system to rescue the main crop where tip burn occurs a few days later. The study mentioned that thanks to early signs of tip burn in the indicator crop, calcium fertilization was applied, leading to increasing yields in a range of 4 to 70 percent (Uno *et al*., 2016). For perennial crops such as avocado, the selection of an indicator crop might be more challenging than for annual crops. Identifying the indicator crop may be reliant on crops that are associated or intercropped with the main orchard, or those present in the areas surrounding the main production area.

It is important to note that to develop and sustain an EWS requires strong stakeholder participation from a range of actors including government, research institutions and local communities. Engagement of avocado producers in the development and design of these systems is crucial to ensure their relevance. Collaboration with research and other public institutions is critical as the amount of data generated by the systems needs to be analysed and processed in order to produce reliable information for decision-making. Early warning messaging also needs to be evaluated regularly and jointly with avocado producers and associations, to ensure that the information provided is targeted to the needs of producers and that adequate response measures are taken following receipt of the messages.

12 Exchange rated used: 1 USD = 0.0016 CFA

4.5 Integrated pest management

Climate risks and impacts addressed: the practice does not address climate hazards directly, but rather the effects of **increased temperatures** and **humidity** in some regions, bringing in new and/or more persistent **pests and diseases**. Co-benefits include the reduction of chemicals, especially highly hazardous pesticides. This can also lead to the **protection of pollinators**, potentially resulting in higher yields.

The practice:

Integrated pest management (IPM) is an agroecological practice that consists of combining several agricultural practices – crop rotation and association, mechanical and biological control – to manage pests and diseases. Pathogens that can be managed through IPM include fungi (e.g. *Phytophthora cinnamomi, Raffaelea lauricola*), bacteria, insects, mites, vertebrates and weeds that damage avocado orchards and fruits at pre- and post-harvest stages as discussed in **Chapter 3**. IPM also helps to replace or minimize the use of synthetic pesticides and herbicides (Garming and Waibel, 2005) and the associated negative risks to human health and environment.

For **crop association**, producers can introduce repellent plants of invasive weeds and malicious insects and pathogens. Some examples used in agriculture for defence against phytophagous insects are Veratrin (*Schoenocaulon officinale*), basil (*Ocimum basilicum*), mint (*Mentha* spp.), lavender (*Lavandula* spp.), sage (*Salvia* spp.), and thyme (*Thymus* spp.) (Moore *et al*., 2006).

Attractant plants can also be integrated to bring in beneficial insects that can serve as natural predators to avocado pathogens and help to increase the presence of pollinators. Some of these plants are Lanta (*Lantana camara*), pigeon pea (*Cajanus cajan*), white clove (*Trifolium repens*), brown hemp (*Crotalaria juncea*), pinto peanut (*Arachis pintoi*), lavender (*Lavandula* spp.) or sage (*Salvia* spp.).

Crop rotation is not feasible for avocado orchards, however, rotating cover crops and crop association can enhance biodiversity in the farms, providing pest protection to the production system (Dufour, 2015). Also refer to the practices on **cover crops** or **agroforestry** in this document. **Figure 14** offers an example of the use of rotational cover crops in avocado orchards in Peru.

Figure 14. *Cajanuns cajan* used as a cover crop and to attract pollinators in an avocado orchard in Peru

© *Westfalia Fruit Peru.*

Biological control methods refer to practices used to manage diseases by inhibiting plant pathogens, enhancing plant immunity, and/or modifying the environment through the effects of beneficial microorganisms, compounds derived from fungi and bacteria, or healthy cropping systems (He, *et al*., 2021). According to Lahlali *et al*. (2022) biological agents such as *Pseudomonas* spp., *Bacillus* spp., *Burkholderia* spp. and *Trichoderma* sp. have been found to be favourable in the fight against pathogens causing foliar and soil-borne diseases like *Agrobacterium radiobacter*, *Erwinia* spp., *Fusarium* spp., *Rhizoctonia solani, Phytophthora* spp. and *Pythium* spp. Some insects can act as predators for aphids, mites, scales or mealybugs such as the predatory ladybird.

It is important to highlight that the inappropriate introduction of species or agents for biological control may have undesired effects on the ecosystem, such as threats to local and native species, and therefore should be carefully researched prior to selection (Teem *et al*., 2020).

Mechanical methods refer to any physical or hands-on control methods, such as using barriers and traps or the manual removal of damaged fruits and leaves. Pruning is one of the most used mechanical methods in avocado systems to control infestation of diseases and insects. For instance, thinning the canopy can prevent caterpillars, greenhouse thrips or mealybugs from migrating to other trees, while reducing their survival. Pruning can also be helpful to prevent the spread of fungal diseases. For example, pruning branches that are close to the ground can reduce pathogen propagules that splash up from the soil when rains occur (Dreistadt *et al.*, 2007). However, care is needed in the timing and method of pruning to not increase the risk of diseases and disorders. For example, it is advised to prune trees when they are dry to reduce the risk of infection in freshly pruned wounds.

Other simple methods to prevent and reduce pathogen spreading include maintaining good hygiene of machinery and equipment, disinfecting tools, and minimizing movement of machinery and vehicles between affected and clean areas (Martín Gil and Aranda Aranda, 2021).

A key feature of IPM is the regular monitoring of orchards to ensure early detection of pests and diseases and monitor changes in their levels. Monitoring pathogens should take place throughout the development of the life cycle of the avocado plant (see **Figure 15**). At fruit setting phase, producers need to look out for fruit spotting bugs, mites, scales and leaf-feeding beetles, which might be more persistent at this stage. During fruit development, fruit spotting bugs, leaf-feeding beetles, mites, scales, thrips, loopers, leaf roller and fruit fly might be more prevalent (Faber *et al.*, n.d.).

Monitoring must be accompanied by the correct knowledge and identification of pests, diseases and weeds that may harm avocado plantations, as well as the beneficial plants and insects that could help combat the pests. Understanding the life cycles and seasonality of pests and disease and invasive species is required in this step. Orchard history, including pest problems and soil conditions, is also crucial for IPM in avocado production as it will allow to anticipate infestation. This is a key component for improving the resilience of the production system.

Figure 15. Soil sampling for the collection of root phytopathogens

© APEAM, A.C.

Box 4. Example of IPM by an avocado company in Mexico

Company or association: Asociación de Productores y Empacadores Exportadores de Aguacate de México (APEAM, A.C.)
Region: Michoacán, Mexico

Climate change does not only include changes in temperature or the intensity and frequency of rainfall. One of the side effects is the emergence or increase of pests and pathogens. In the avocado producing area of Michoacán, the last decade has shown a significant increase in the damage caused by pest insects such as beetles of the species *Xyleborus glabratus* and *Euwallacea californicus*, as well as by different species of thrips and mites. This is coupled with the incidence of root rot caused by the phytopathogen *Phytophtora cinnamomi*.

To counteract these pests and pathogens, the research unit of APEAM, A.C. has implemented a project to monitor beetles, thrips, mites and phytopathogens. It also seeks to find natural measures for controlling these such as natural enemies or antagonistic organisms. Through these actions the association reports having:

- avoided the loss of avocado trees;
- developed sustainable and specific control measures for these pests and pathogens;
- trained technicians and producers in the progress of these projects; and
- reduced the probability of occurrence or large outbreaks of these diseases and pests.

It is important to note that the use of IPM practices may tolerate low pest numbers on plantations, as well as the discrete application of agrochemicals. The latter should be used to address specific pests, diseases or weeds in a measured and targeted way and only when it is necessary (Dreistadt *et al*., 2007). In some instances, IPM practices may not be adequate for the control of certain insects and pests where zero tolerance of these species in orchards is required to meet the phytosanitary requirements of importing countries.

Finally, IPM programs work to monitor pests and accurately identify them, so that appropriate decisions can be made for management in accordance with the action thresholds (see **Box 4**). Monitoring and identification of pests also helps to reduce the possibility that pesticides are used when they are not needed or the wrong type of pesticide is used (ICA, 2012). However, it is critical to recognize that monitoring and response action are tied to the economic capacity, access to information, and knowledge of producers.

4.6 Integrated management of agricultural water resources

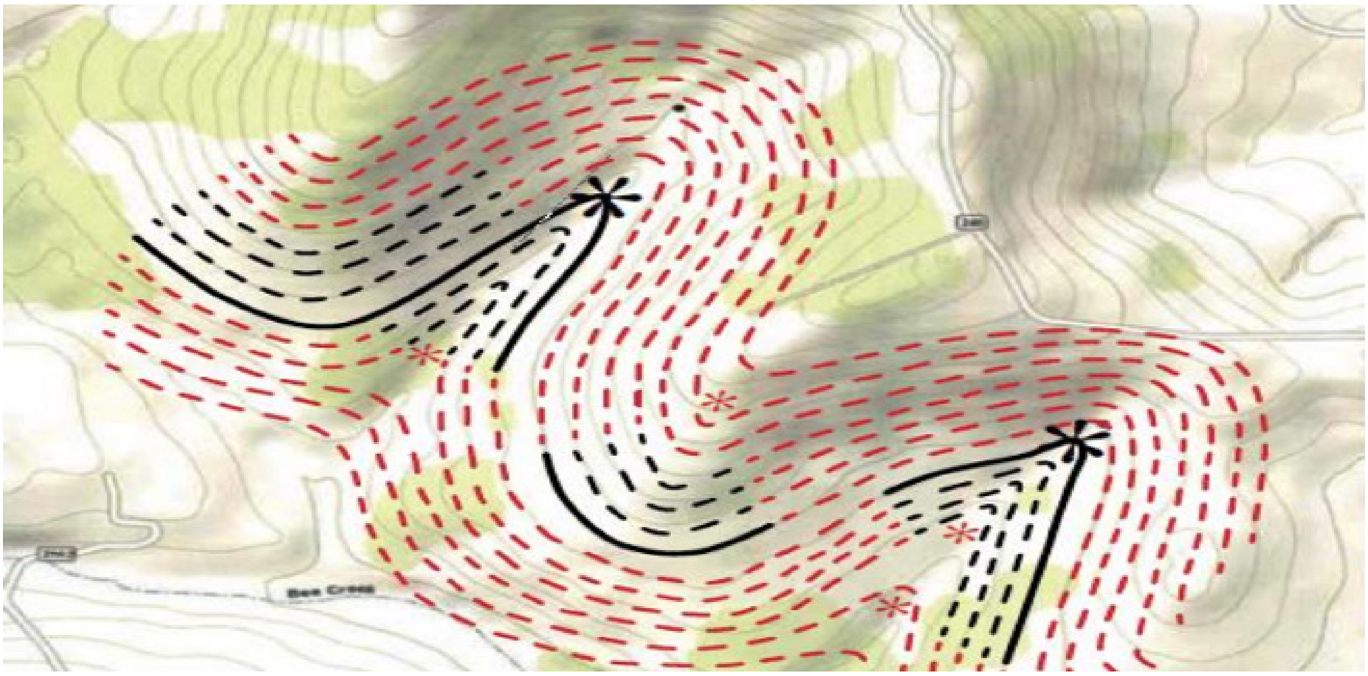
Climate risks addressed: drought, intense rains, changes in rainfall patterns and soil erosion. Other benefits include reduction in the use of external inputs, such as fuel in irrigation systems and agrochemicals. Social benefits include improved water availability for household use and production.

The practice:

Integrated management of agricultural water resources is a process that promotes the coordinated development and management of water, land and related resources to maximize the efficiency in water consumption and protect ecosystems. The practice has important agricultural water-saving potential by combining agricultural techniques, infrastructure investments and low water-use techniques (Zhang and Guo, 2016).

An example of integrated water management is contour planting, mainly **keyline design** (**Figure 16**). The practice consists of a combination of water conservation and regeneration of soils. The system is composed of planting lines and channels created in the soil by using minimum tillage practices, aiming to improve water infiltration, aeration, reduce water erosion and stimulate root growth (Bessert, 2022). Keyline design can be divided in two types. Keyline ploughing which creates parallel cultivation lines that considers the special geographical features that guide water to run up on higher elevations instead of gathering in the valleys. Another type of keyline design is to combine grazing and tree rows, or to cultivate hillslopes through terracing (Johansson, Brogaard and Brodin, 2022).

Figure 16. Keyline design as an example of for integrated water management in agriculture



Source: **Bessert, L.** 2022. *Keyline Design- water management of agricultural landscapes: Key for Regenerative agriculture?* University of Kassel.

The practice seeks to establish reference contour lines that does not result in a cultivation pattern that is too steep which can enable water erosion. The objectives of keyline planting include shielding the soils against the effects of drought or intense rains; distributing water evenly; and converting the soils into large water stores and carbon sinks. The practice is one of the most effective conservation agriculture practices that helps to retain soil, increase water infiltration, and keep the water uniformly in the land to recover or maintain its fertility (del Carmen Ponce-Rodríguez *et al*., 2021). It is important to note that the practice does not only help to address water risks related to deficit, but is also effective for draining excess water, both issues particularly relevant to the avocado sector in different producing regions.

Agroforestry systems are especially suitable for the implementation of Keyline design (see section on **agroforestry** for avocado production). In these systems, avocado and other tree species are planted along the swales on the descending site. Thereby, the water availability for tree roots is improved particularly on steeper slopes, while soil erosion is prevented (Gerhardt, 2021). The practice can guide the design of cultivation patterns in specific production sites, but can also be used to redesign whole landscapes, making these more resilient to climate change and impacts.

Although research is not available for avocado production, the use of integrated approaches to manage water in forest systems in Mexico have shown positive impacts on water efficiency and production. The approach has increased the efficiency of rainfall use between 10 and 15 percent and contributed to the survival rate of planted species by reducing the water stress in the early development of the planted *Pinus Pseudostrobus Lindl* (Zacarías Calderón, 2017).

Overall, integrated agricultural water management include practices such as (FAO, n.d.):

- Rainwater harvesting, soil and water conservation, **deficit and supplementary irrigation use**, among others, in order to increase the availability of rainwater available to crops.
- On-farm water management to minimize water losses by evaporation (e.g. use **mulching and cover crops**, **windbreaks**).
- Use of crop varieties resistant to droughts and high humidity (see section on **plant breeding**).
- Use of improved cropping systems and agronomic practices, such as minimum tillage or key line ploughing.
- Use of non-conventional water (e.g. harvested rainwater or treated wastewater) in non-agricultural activities, such as for cleaning machinery and equipment.
- Evaluation of rainfall patterns to determine quantity and quality available for agriculture use and design crop system, particularly in avocado production systems that grow in combination of other species (**agroforestry** and intercropping systems, **cover crops**). Monitoring rainfall also helps in the decision-making of specific processes such as the timing in the application of fertilizers and pesticides.

When taking an integrated approach to manage agricultural water it is important to know the soil properties and water needs, as this will shape which agronomic practices and other infrastructure work might be needed.

Before adoption, it is important to identify the environmental impacts related to the implementation of infrastructure as it might generate risks to local ecosystems. For instance, when harvesting and storing water, the amount of time in which water will be stored, the content of organic matter present and the potential for fertilizers to be transported through runoff should be considered. Exposing stored water to solar radiation may also affect the water properties with potentially negative effects on soil and ecosystems when using the water for agriculture or other uses.

4.7 Mulching and cover crops

Climate risks and impacts addressed: soil erosion from intense rainfall and wind, low humidity, competition with weeds for nutrient uptake. Permanent soil cover can also protect seedlings and roots from **frost, drought, changes in rainfall patterns** and **sudden temperature changes**. Other beneficial impacts include improving soil structure and fertility and reducing pest incidence by interrupting the pest cycle through adding other crops. This can also reduce the need for agricultural inputs such as fertilizers and pesticides, while **protecting pollinators**. Good nutrient management through these practices can also help producers to prevent the incidence of **alternate bearing cycles** and **reduce GHG emissions**.

The practice:

Mulching and cover crops are conservation practices used to regenerate and protect the soil structure and health (Oloo *et al.*, 2013).

Soil mulching is mainly divided into natural or organic mulching and synthetic mulching. **Organic mulching** is composed of vegetative matter or other crushed material (e.g. crop residues, straw, cut grass or leaves) as a loose layer of crop residues spread over the soil surface. Dry leaves are widely used in forest areas and where trees are abundant, thus this measure could be suggested for overwinter mulch (as dry leaves might not be available in springtime) and for avocado plantations established near forests. Composted leaves or the use of small branches and wood barks can be combined with dry leaves to improve the quality and reduce the loss of dry leaves when wind is present (Ranjan *et al.*, 2017). Straw is also a good mulching material as it also provides insulation, water penetration and weed control. According to Dreistadt *et al.* (2007), the use of organic mulch, such as woodchip, can reduce the incidence of *Phytophthora cinnamomi* root rot, one of the most important diseases of avocado. The authors also mentioned that mulching can decrease the incidence and severity of stress-related diseases and disorders such as black streak. **Figure 17** illustrates the use of straw as mulch in young avocado tree plantations.

Synthetic or inorganic mulches are formed by materials, such as plastic sheets or rocks, and that cannot be degraded by soil organisms. Although these are more long-lasting measures than organic mulches, implementing synthetic materials requires deliberation in the use and disposal of plastics to prevent potentially negative ecosystem impacts related to plastic waste and pollution.

Considerations for using **organic mulching** include the replenishment of the organic matter, as it decays over time due to decomposition. However, the cost of using organic mulches tends to be low as materials are cheap and locally available. **Synthetic mulch** might be more expensive to implement but more durable, though they are usually non-recyclable and therefore not environmentally friendly.

Figure 17. Utilization of organic mulching and cover crops (*Trifolium repens* L.) in avocado orchards in Peru

© *Westfalia Fruit Peru*

Cover crops is another practice that provides an additional protection to avocado plants and roots with co-benefits on ecosystems. Cover crops are also one of the simplest and most economical sources of nutrient-rich organic matter available to producers. When establishing avocado seedlings, cover crops can reduce nutrient leaching into the soil by absorbing available nutrients that are not yet accessible to nascent root system of avocado trees (López-Silva and Vega-Norori, 2004). In the growing phase, cover crops help to maintain soil moisture and temperature, controlling erosion and suppressing invasive weeds.

Some of the most used cover crops in tropical and subtropical plantations are tropical kudzu (*Pueraria phaseoloides*), which establishes slowly reaching full ground cover after 10 months; tick clover (*Desmodium ovalifolium*), which is tolerant to shade from trees; sunn hemp (*Crotalaria juncea*); hairy vetch (*Vicia villosa*); cowpea (*Vigna unguiculata*); white clover (*Trifolium repens L.*); and maize (*Zea Mays*). Other crops could include *Arachis* sp., *Calapogonium* sp., *Mucuna pruriens, M. bracteata, Canavalia ensiformis, Dolichos lablab, Vigna radiata, Vigna unguiculata* and *Arachis pintoi* (Mary, 2020). Native and local species should be prioritized to mitigate potential negative ecological impacts. **Figure 17** shows how *Trifolium repens L.* has been used in avocado plantations in Peru.

When using **cover crops**, attention should be given to the selection of species, to avoid competition with avocado plants or the potential for attracting pests or diseases that can affect avocado roots and trees. Also, when using these practices, moisture levels need close monitoring as high humidity and poorly drained soils can restrict oxygen in the root zone, creating an environment conductive to the invasions of diseases and pests.

Box 5 provides an example from Peru of the trial of various cover crops in commercial avocado plantations.

Box 5. Use of cover crops to minimize soil erosion and water evaporation in Peru

Company or association: Westfalia Fruit
Region: Peru

Increased salinity, soil erosion and drought risks have been observed in the coastal area in Peru where most of the avocado production takes place. To address these issues, Westfalia Fruit Peru is testing the use of different cover crops such as beneficial forages and native plants. Some of the plants used as cover crops and reported benefits are:

- Maize (*Zea mays*): helps to reduce salinity in soil and when added as a cover mulch it can reduce moisture loss. Also, it serves as a windbreaker to reduce damage to trees.
- Pigeon pea (*Cajanus cajan*): helps as a green manure, by cutting the foliage and adding it to the soil it increases soil organic matter.
- Vetiver (*Chrysopogon zizanioides*): is one of the best crops to be used as mulch given its adaptability. It also helps to keep the moisture in the soil and lower its temperature.
- White clover (*Trifolium repens*): adding it to the sides of the orchard near the trees helps to maintain soil moisture and lowers soil temperature.
- Sunn hemp (*Crotalaria juncea*): creates symbiosis with nitrogen-fixing bacteria that live in root nodules; flowers also help to attract pollinators.

The use of legumes, such as pigeon pea, white clover and Sunn hemp support the increase in nitrogen availability for avocado, potentially reducing the amount of nutrient additives needed in the plantations.

Mulching and cover crops have positive impacts on soil structure and nutrient content (Oloo *et al*., 2013). For instance, organic mulch decomposes over time, adding organic matter into the soil and preventing nutrient leaching. Cover crops, such as legumes (e.g. white clover, beans, alfalfa) have positive effects on nitrogen fixation, improving soil nutrient availability (Ranjan *et al*., 2017). Legumes also contribute to the proliferation of microhabitats for many microorganisms, insects, reptiles, rodents and birds, favouring earthworm populations by improving aeration and the rate of soil infiltration (López and Vega, 2004).

These practices can also be used as a tool for weed control as they minimize the presence of pathogens and pests in the soil, while enhancing the presence of beneficial organisms and neutralizing pollutants (Sarminah *et al*., 2021). For instance, mite damage could be reduced due to the lower presence of dust and drought stress brought by improved soil moisture. Lastly, improved soil management through mulching, cover crops and composting, as well as the optimization of the number of trees per farm (less trees per hectare) can also have a positive effect on productivity through improved fruit retention (Nyakemiso *et al*., 2021).

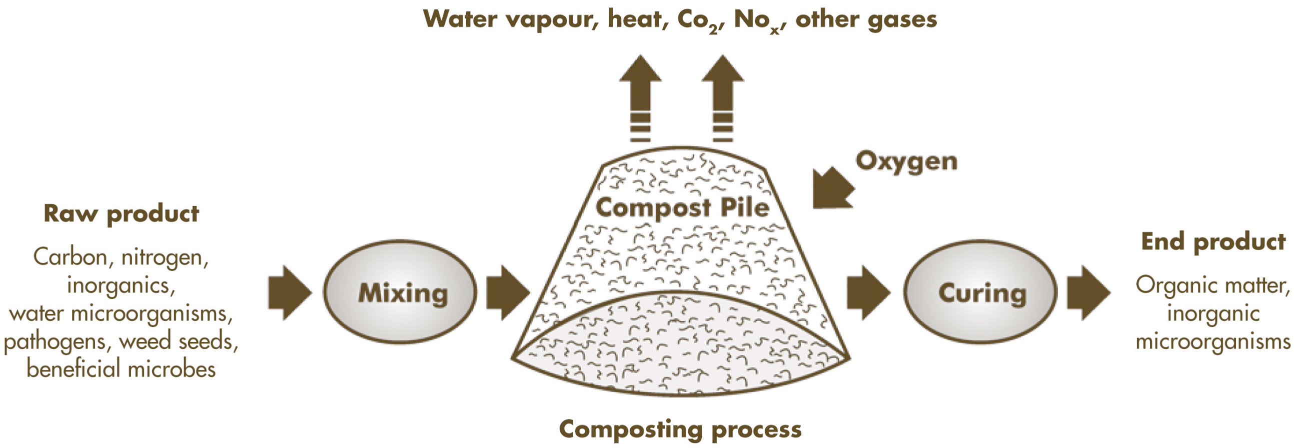
4.8 Organic fertilizers (composting, biofertilizers)

Climate risks and impacts addressed: soil erosion from intense rainfall and wind, drought, water shortage and changes in rainfall patterns. Organic fertilizers can also help minimize the effects of salinization. Other co-benefits include the reduction in synthetic fertilizer usage and the protection of **pollinators**. Good nutrient management can also help producers to prevent the incidence of **alternate bearing cycles**. The incorporation of organic fertilizers is in many cases also necessary to comply with organic certification schemes.

The practice:

Organic fertilizers are used to improve the physical, biological and chemical characteristics of the soil. **Composting** is the most commonly used organic fertilizer, created by using organic waste from the remains of production and processing of agricultural products, manure, slurry and/or household waste (food leftovers and garden matter) as primary materials to create high-nutrient fertilizers. Composting can also be beneficial in areas with high exposure to rain or wind erosion. In avocado production, generating compost out of production residues and **by-products** (e.g. guacamole, oil) can have important implications for the reduction of agricultural waste (González-Fernández *et al*. 2015) and climate change mitigation. **Figure 18** illustrates the basic composting process.

Figure 18. Material flow for composting process



Source: **Livestock Engineering Unit & Environmental Practices Unit.** 2005. Manure composting manual. Alberta – Agriculture, food and rural development. Canada. www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex8875/$file/400_27-1.pdf?OpenElement

Biofertilizers are prepared with microorganisms (bacteria, fungi, algae, leguminous plants, azolla, grasses and others) which are applied to the soil and/or plant. Microorganisms can be classified in two groups. The first one includes microorganisms that can synthesize substances promoting plant growth, fixing atmospheric nitrogen, solubilizing inorganic iron and phosphorus, and improving tolerance to drought stress, salinity, toxic metals and excess pesticides by the plant. The second group comprises microorganisms capable of diminishing or preventing the negative effects of pathogens (Armenta-Bojórquez *et al.*, 2010).

The use of compost and biofertilizers is one sustainable alternative to reduce the use of chemical fertilizers and nutrient-additives and the associated negative effects on the soil and crops (Larios Guzmán *et al.*, 2008). As organic fertilizers build up a healthy soil system, they can help to increase tree performance and yield by enhancing nutrient uptake. In South Africa, composting was noted to increase root growth and reduce stress during adverse conditions, which in turn increased avocado yield (Mohale *et al.*, 2022).

A study conducted in Mexico showed that the number of flowers and fruit setting was significantly higher (by 133 percent) when organic fertilizers such as mycorrhizae[13] (*Glomus* sp.) and/or earthworm liquid humus (*Eisenia foetida*) were applied, compared to trees where synthetic fertilizers were used (Hernández-Valencia *et al.*, 2021). The study indicated that the higher nutrition content – mainly boron and nitrogen – found in organic fertilizers were the main contributing factors to these results.

[13] The term mycorrhiza refers to the role of the fungus in the plant's root system, by creating a symbiotic association between a fungus and a plant. The association contributes to the plant nutrition by providing mineral nutrients and water to the host plant, and also to soil chemistry and biology.

The study also observed similar yields between chemical and organic fertilizers, however, larger fruits were obtained in trees where organic fertilizers were used. Another study from Chile also depicts favourable effects of bacterial inoculation to not only stimulate plant growth, but also to mitigate the effects of water shortage and salt stress on avocado tree seedlings (Barra *et al.*, 2017).

Organic fertilizers are particularly useful in soils that have been overused and present degradation processes, such as low organic content or salinization problems.

Considerations for use of organic fertilizers include proper preparation and safety of the products. In the compost production process, the levels of moisture, nutrients and temperature must be controlled to ensure proper decomposition of the organic matter and to reduce the presence of potential pathogens. The use of animal or human organic waste without prior treatment may pose health risks. To avoid these, maintaining high temperatures (60 °C to 65 °C) during the preparation process can ensure the safety of the compost (UN Environment, 2015).

4.9 Plant breeding

Climate impacts addressed: heat stress, solar radiation, drought, rainfall variability, frost and cold stress. Through plant breeding it is possible to further improve the quality of the fruit and lower perishability due to increased resistance to post-harvest diseases. The reduction of pre- and post-harvest waste also has important climate change mitigation potential.

The practice:

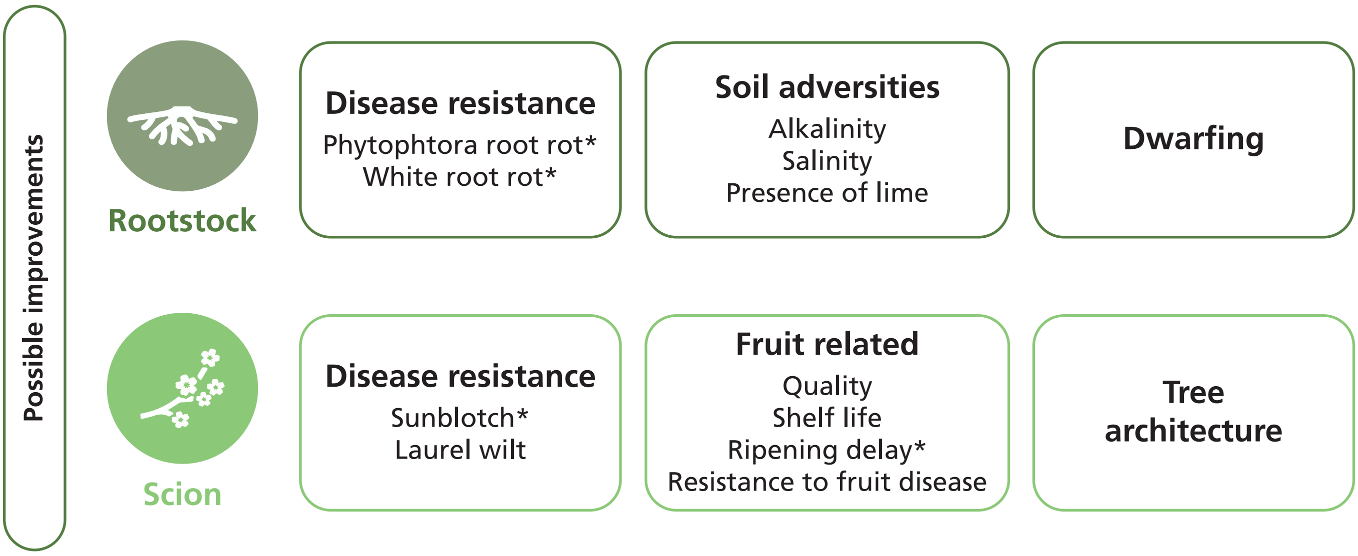
Plant breeding is the process of developing new crop varieties with the desired traits, including features that can help plants to adapt better to the biotic and abiotic stress conditions (**Figure 19**). Plant breeding has the potential to increase the resilience of the crop in the face of climate change. Breeding varieties with greater resistance to different stresses may reduce reliance on external inputs or resources which in turn, can reduce carbon emissions associated with the consumption of fossil fuels and reduce production costs (Brookes, 2022).

In avocado production, breeding programmes have focused on developing rootstocks tolerant to *Phytophthora cinnamomi* root rot, soil salinity, and calcareous soils among others. Breeders have also concentrated efforts on selecting cultivar offshoots with high and stable yields (Nieto Flores, 2017), as well as protecting the quality of the product at the pre- and post-harvest stages (Tamayo-Ramos *et al.*, 2022).

The development of improved plants is a long and expensive process that requires participation from both state and non-state actors. According to the Official Gazette of Plant Breeders' Rights of the Secretariat of Agriculture and Rural Development (SADER) of Mexico, only 14 plant breeders' rights have been granted since 1998, and since 2014 no new varieties have been registered. To maintain production in the scenario of rapid climate change, growers require new varieties with greater resistance to environmental conditions. Given the urgent need to accelerate the genetic improvement of avocado, it is essential to join efforts between different actors and use the most innovative techniques.

This section offers some general findings from the literature on avocado breeding for certain traits that may also support climate adaptation or reduce impacts of climate change on the plant. According to Tamayo-Ramos *et al*. (2022), there are some main areas in which biotechnological breeding of avocado has taken place to date that could lead the way for future research as show in **Figure 19**. The examples are non-exhaustive as work is ongoing in this area to develop state-of-the-art technologies for plant breeding, and research on new varietal development takes time. In many cases, nascent evidence is just being generated.

Figure 19. Possible avocado traits for transformation through genetic breeding



Note: Areas where some research has been developed are marked with an asterisk (*).

Source: **Tamayo-Ramos, D.I., Salazar-González, J.A., Casson, S.A. & Urrea-López, R.** 2022. Old and new horizons on Persea americana transformation techniques and applications. *Plant Cell, Tissue & Organ Culture*, 150(2): 253–266. 10.1007/s11240-022-02268-7

A common technique used in agriculture to improve different agronomic characteristics of plants, such as yield and vigour, as well as tolerance to different stresses is **grafting**. The technique is widely used for vegetative propagation, especially in perennial fruit crops (Loupit and Cookson, 2020). Grafting experiments with the "criollo" tree seeds have shown to provide, via seedling rootstocks, up to 35 percent of genetic gain for relevant yield traits for the Hass variety, including the total number of fruits per tree, fruit diameter and length, fruit and pulp weight and branching (Cañas-Gutiérrez *et al.*, 2022). On the other hand, another study showed the "Fuerte" variety is not a suitable breeding parent for regions with Mediterranean agro-climatic conditions (Bergh, 1976). The University of California (2023) also showed that clone selection in orchards repeatedly exposed to frost stress can be a starting point to create more frost-resistant varieties.

Considerations for using breeding practices include investment costs required for research to both identify genes that provide the desired characteristics in avocado plants and testing the new varieties in real orchard conditions. As previously mentioned, plant breeding requires a long-time horizon, thus this practice should be perceived as a long-term adaptation effort. **Box 6** provides an example of the work that researchers in Mexico are doing to improve avocado varieties in the future.

Box 6. Plant breeding practices in Mexico

Company or association: Centro de Investigación y Asistencia en Tecnología y Diseño del Estado de Jalisco (CIATEJ)
Region: Jalisco, Mexico

Researchers from CIATEJ in Mexico and the University of Sheffield in the United Kingdom, reported the first transient genetic overexpression in avocado plant leaves, overexpressing a reporter to optimize critical parameters of the process. The researchers used a transient transformation strategy, that is, they did not modify the avocado genome, nor did they generate stable transgenic organisms. In other words, using biotechnology in the process, but not in the product. In this way, the research provides a new alternative that will support the work of the research community that studies this species, and at the same time, will promote genetic improvement through the application of molecular biology and genetic engineering. This could offer farmers improved avocado varieties in the near future that would allow producers to respond to an increase in demand in an environmentally sustainable manner.

The results were published in the scientific article "In-planta transient transformation of avocado (*Persea americana*) by vacuum agroinfiltration of aerial plant parts", in the Plant Cell, Tissue and Organ Culture scientific journal (Salazar-González *et al.*, 2023), which can be accessed in the following link: https://doi.org/10.1007/s11240-022-02436-9

4.10 Protection of pollinators and beekeeping

Climate impacts addressed: the practice does not address climate hazards directly, but rather the effects of **extreme temperatures, environmental degradation and loss of biodiversity**, affecting pollinating activity. A co-benefit of beekeeping is the provision of an alternative source of income (e.g. commercialization of honey, propolis, royal jelly, apitoxin and pollen) in the event of crop loss or damage, increasing the general resilience of avocado producers.

The practice:

The protection of pollinators is crucial in avocado orchards, as production is highly dependent on pollinating activity influencing fruit set and yields.

Worldwide, the Western honeybee *Apis mellifera L.*, is reported as the insect with the highest pollinating activity of avocado (Vasquez *et al*., 2017) followed by stingless bees (Meliponini) and blow flies (*Calliphoridae*) (Dymond *et al*., 2021). In Mexico and Central America, stingless bees and the Mexican honey wasp (*Brachygastra mellifica Say*) were identified as the primary pollinators. In tropical and sub-tropical African producing regions, tropical African latrine blowfly (*Chrysomya putoria*), drone fly (*Eristalis tenax*), hover fly species (*Phytomia incisa W.*) and polistine wasps (*Polistes* sp.) have been classified as potential pollinators supplementing pollination from honeybees (Nyakemiso *et al*., 2021; Nyakemiso *et al*., 2022; Sagwe *et al*., 2022). In New Zealand, moth species (*Ichneutica mutans*, *Ichneutica ustistriga*, *Epyaxa rosearia*, *Rhapsa scotosialis*, *Phrissogonus laticostatus*) also appear to display a high capacity to carry avocado pollen grains and could complement pollination services provided by bees (Buxton *et al*., 2021).

Pollination deficit has been observed due to extreme temperatures (very high or very low) and heavy reliance on agrochemical use, affecting the size of pollinators' population and their health as discussed in **Chapter 3**. However, the pollination deficit could be compensated by different measures including the implementation of *A. mellifera* colonies in avocado orchards, along with health treatment measures (see **Figure 20** for an example of beehives). Vásquez *et al*. (2011) conducted a study using direct pollination with *A. mellifera* in four varieties of avocado in Colombia, incorporating an average of 3 to 4 hives per hectare. The results indicated a production increase between 21 and 96 percent. Another study found similar effects on increased number of fruits per tree (54 to 68 percent) after establishing four to six beehives per hectare (Peña and Carabali, 2018). The study found that the presence of bees also had important effects on fruit weight leading to the production of heavier avocados. These findings have important implications on marketable products and income for producers.

Figure 20. A group of beehives in Mexico

© FAO/Florita Botts.

Considerations for implementing honeybee colonies include the need for water availability in the areas surrounding the avocado orchards. If not naturally available, water containers should be installed to ensure the correct hydration of bees. The vegetation surrounding the colonies and production areas will determine the density of the colony, however, three to six beehives per hectare may be adequate in avocado orchards (Peña and Carabali, 2018; Vásquez *et al*.,2011). Also, the addition of some plants to increase attraction to avocado flowers, such as the *Citrus* spp., and species of the mint (*Labiatae*), daisy (*Fabaceae*) and mustard (*Brassicaceae*) can be beneficial (Ish-Am, 2005). The position of the hives should account for the wind activity, as strong wind can challenge bees' ability to exit and enter the hive (SAGARPA, n.d.). Beekeeping requires technical knowledge for the implementation of the hive, as well and knowledge on cleaning and disinfection measures are also needed to preserve the health of bees.

Protecting or restoring natural habitats in agricultural landscapes could support native pollinator communities and reduce the dependence on honeybees for avocado pollination. This could be done for instance, through changes in agricultural practices including the reduction of agrochemical use (see **IPM section**) and introduction of plants enabling pollinating activity. Such plants include white mustard (sinapis alba), west Indian Lantan (*Lantana camara*), twin-flowered cassia (Senna pallida), billygoat weed (Ageratum conyzoides), and squarestem (*Melanthera aspera*) (Jimenez and Arrieta, 2018), among others.

The selection of the plant species to attract pollinators should be region-based to prevent non-native plant species from becoming invasive. Likewise, the introduction of foreign pollinator species can potentially outcompete pollinators native to the production areas with detrimental impact on local biodiversity.

An example from Mexico on efforts to increase and preserve pollinator populations is given in **Box 7**.

Box 7. Protecting pollination populations through an integrated approach in Mexico

Company or association: Asociación de Productores Exportadores de Aguacate de Jalisco, A.C. (APEAJAL)
Region: Jalisco, Mexico

In 2018, the Association started a program of reforestation of native trees around the productive area, encouraging producers to include plants that attract pollinators with the aim to help to conserve and increase the pollinator population in the production area. Ecosystem benefits are reported since pollinators help the reproduction of plants and flowers, and some pollinator-attractant plants also prevent the erosion of soil and improve biodiversity. On the economic side, the Association reports that bees and other pollinators have helped to increase the productivity of the avocado tree and therefore the potential amount of fruit to be traded.

APEAJAL, through the Committee for the Conservation of Pollinators of Jalisco, collaborates with research institutes, avocado producers, berry producers, beekeepers and municipal governments in the implementation of projects to identify pollinating insects that provide their services in agricultural fields, and in the dissemination of practices that promote the preservation of the population and health of pollinators in avocado plantations.

4.11 Shade nets

Climate impacts addressed: heat stress, solar radiation, hail, frost, cold stress and **strong winds**. Other benefits include protection against flying pests (insects, birds, bats), increased production of higher-quality fruit and marketable yields, and reduction of post-harvest waste. The reduction of post-harvest waste also has important climate change mitigation potential, and the overall benefits of shade nets may increase system resilience. The control of solar radiation and sudden high temperatures can also help producers to minimize the incidence of **alternate bearing cycles**.

The practice:

Solar radiation in some avocado producing regions, such as Israel and South Africa, is high with increasing trends affecting optimal avocado tree growth and development. Nets can provide physical protection to trees and protect fruits from extreme environmental hazards, such as excessive solar radiation, wind, hail, frost, and/or flying pests (insects, birds, bats) (Shahak, 2014). Nets in avocado orchards can also enhance the post-harvest quality of the fruits, increasing shelf-life and reducing waste (Tinyane, Soundy and Sivakumar, 2018).

Different types of nets can be used in avocado orchards, which can be classified by colour and density. The colours aim to manipulate the light quality to stimulate specific responses in plants affected by light and temperature depending on the colour used (red, yellow, green, blue, white, grey/silver or pearl). See **Figure 21** for an example of different colour shading nets. The density is used to control the amount of light that passes through the net. The nets are usually made of plastic enhanced with chromophores and elements that disperse and reflect sunlight (Sivakumar, n.d.).

Evidence from Israel shows that silver-net shading at 60 percent[14] reduces direct light density by about 65 percent, as well as air and leaf temperatures by up to 4 °C in "Pinkerton" avocado trees (Alon *et al.*, 2022). The study also reported that net use improved photosynthetic performance under extreme heat conditions. Thus, the reduction in temperatures and protection offered by nets may significantly reduce the fruit and tree damage caused by heat stress. Other studies showed that covering "Reed" avocado trees during the winter with silver 50 or 70 percent shading nets can also lessen cold stress in winter (Chernoivanov *et al.*, 2022). Thus, shading nets can also serve to mitigate cold stress in commercial avocado orchards (see section on **anti-frost systems**).

Figure 21. Colour shading for sunlight control in avocado plantations

Source: **Tinyane, P., Soundy, P. & Sivakumar, D.** 2018. Growing 'Hass' avocado fruit under different coloured shade netting improves the marketable yield and affects fruit ripening. *Scientia Horticulturae*, 230: 43–49. https://doi.org/10.1016/j.scienta.2017.11.020

[14] The net shading percentage refers to the density of the net, i.e. how closed or open they are to allow the light to go through it. The higher the percentage, the less light is allowed to pass.

In South Africa, shade netting was found to reduce canopy temperature by about 5 °C in the afternoon, whereas in sub-zero winter nights, the nets were able to increase the temperature by about 2 °C (Blackey *et al.*, 2015). The research also showed a positive correlation between net use and higher soil moisture. A different study showed that blue and white netting significantly contributed to reducing the incidence of sunburns and increased protection from wind and hail damage. Red-coloured netting was found to delay fruit ripening and the incidence of anthracnose after harvesting (Tinyane, Soundy and Sivakumar, 2018), resulting in a decrease of post-harvest losses. Overall, netting was favourable to improve external fruit quality, with the potential of increasing Class 1 Hass avocado production by over 10 percent (Stones, van Rooyen and Köhne, 2017), thus expanding the marketable yield potential.

However, it is important to consider that high-density shading nets could have undesired effects on tree growth in the long term and could potentially affect yields by stimulating vegetative growth over productivity. Thus, canopy management (e.g. through regular pruning), net placing (at least one meter away from the canopy) and net colour and density should be carefully considered to produce positive results (Stones, van Rooyen and Köhne, 2017). Using nets also requires deliberation on adequate pollination management, since covered trees can restrict pollinating activity by bees and other insects. Introduction of bees and plant attractant pollinations may address this issue (see section of **protection to pollinators and beekeeping**), as well as opening nets to ensure pollination activity can occur.

Lastly, as nets are made of plastic, companies introducing these should ensure correct management and disposal of plastic and other inorganic materials to avoid unintended environmental impacts.

4.12 Sustainable forest management

Climate risks and impacts addressed: frost, drought, strong winds, flooding, landslides, intense rainfall, rainfall variability, extreme heat and fire. Other co-benefits include ecosystem services such as climate and water regulation, soil regeneration, erosion prevention, nutrient cycling, protection of pollinators and reduction of risk factors that stimulate the alternate bearing cycle. Climate change mitigation through carbon capture and storage is another key advantage. The practice also aids the reduction of climate risks that may be noticeable outside of the managed forested area, such as water availability.

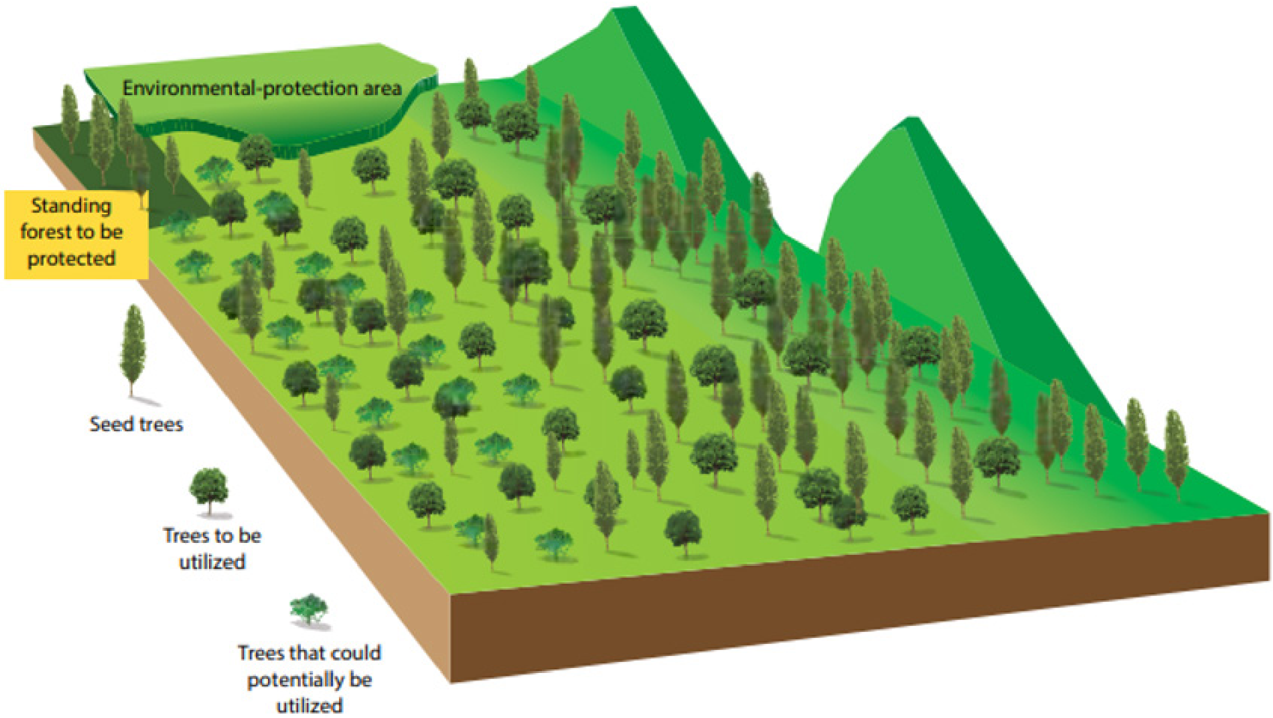
The practice:

While some avocado plantations already take place near forestland, land use change and deforestation are high-risk factors as producers seek out more suitable areas for production in response to climate change and international market demand. **Sustainable forest management (SFM)** is an adaptation measure that seeks to preserve forests and biodiversity, while promoting productive activities and local community development.

SFM planning should aim to maintain the capability of forests to produce a range of wood and non-wood forest products and services on a sustainable basis (European Commission, 1998). SFM can enable continued avocado production in more suitable areas, while actively seeking to eliminate the risk of deforestation, restoring forest cover and enhancing carbon sequestration. This is achieved through practices like reduced logging, natural forest regeneration promotion (selective pruning and clearing), respecting conservation areas, protecting seed trees, conducting a tree inventory and mapping commercial trees, and fire protection (UN Environment, 2015). **Figure 22** highlights how SFM can be visualized in practice.

SFM should not be perceived as an endorsement for agricultural expansion into forestland, but rather as a resource to be used for avocado producers, associations and companies whose activities already take place in forest areas, aiming to improve the sustainability of their operations.

Figure 22. Diagram of managed forest including the different tree species and forest sub-areas



Source: **UN Environment.** 2015. *Microfinance for ecosystem-based adaptation measures – Options, costs and benefits*. Panama.

In the case of avocado cultivation, both producers and local communities should work together to implement SFM in forest regions where production takes place. The practice can be applied to regions and areas that already suffer from or are at risk of forest degradation at any level. Some general SFM principles are identified to implement this practice (IMFN, 2019; CCMSS, 2010):

1. **Identify and define the area to be managed.** This can be based on administrative or ecological boundaries or be guided by the issue that needs addressing (e.g. agricultural production and expansion, restoration). The selected site should be mapped, and a forest inventory made to identify the areas to be dedicated for production, for protection (including water bodies) and for restoration.

2. **Identify the stakeholders to be involved in the development, validation of the management plan and in its implementation.** Stakeholders should include key land users (e.g. indigenous peoples, local communities, avocado producers, logging industry), forest managers and other interested parties (e.g. NGOs, subnational and national governments). The different stakeholders can be mapped through a stakeholder analysis to identify the power dynamics and interest in achieving the SFM purpose.

3. **Commit to sustainability and governance.** The practice is based on the recognition of land tenure and governance, sustainable forest use and management, and community participation and commitment. Thus, a clear establishment of rights and safeguards for forest and land use among the community, Indigenous Peoples (if present) and other forest users must accompany this. If Indigenous Peoples are present in forest areas, then a process of free, prior and informed consent (FPIC) should be conducted to allow them to give or withhold consent to a project that may affect them or their territories. The Voluntary Guidelines on Tenure can also serve as reference to set out principles and internationally accepted standards for practices for the responsible governance of tenure of land and forests.

4. **Identify the main risk(s) to be addressed.** The identification of the most urgent risk(s) related to climate, environmental degradation or other social–economic issues will guide the SFM strategy to address them.

5. **Classify the commercial and protected species and develop a forest management plan.** The forest management plan should be developed based on the classification of species by commercial group (i.e. avocado and other timber and non-timber forest products), species to be utilized and protected, and the administrative division of the area (see **Figure 23**). The management plan should be accompanied by a work plan along with the identification of the financial resources required to achieve the strategic direction.

6. **Establish a monitoring and evaluation (M&E) system** to allow tracking progress and assess the success of the SFM implemented. The system will also help to address issues when they arise, support decision-making and enhance accountability. The learning generated can also help to scale-up and out successful strategies. The International Model Forest Network offers resources and templates to develop an M&E system for SFM.

7. **Communicate progress and results** with all stakeholders involved in the SFM to improve transparency, accountability and engagement.

Figure 23. Forest protection and avocado production in Michoacán, Mexico

© APEAM, A.C.

Considerations for the implementation of SFM include deliberation in the harvesting levels of both wood and non-wood forest products to prevent forest degradation and excessive nutrient extraction. In case the use of nutrient additives and pest management measures are needed, these should be applied in a controlled manner and with due consideration to the environment (European Commission, 1998). Attention to the availability of adequate infrastructure (roads, bridges, skid tracks) is required to ensure efficient provision of products while lessening negative impacts on the environment. An example of a reforestation program in Mexico is given in **Box 8**.

Box 8. Reforestation programme in Mexico in collaboration with local communities

Company or association: Asociación de Productores y Empacadores Exportadores de Aguacate de México (APEAM, A.C.)
Region: Michoacán, Mexico

APEAM started an annual reforestation programme in 2011 that seeks to strengthen the natural biodiversity of Michoacán and aims to develop native tree planting activities, mainly coniferous in the avocado producing regions. Since 2018, the program was modified and included in a comprehensive system that aims to reforest areas of high ecological relevance and aquifer recharge, in which all the avocado producers within the Association partake. The project includes restoration actions and helps producers to make improvements in the forest areas where orchards are implemented or in neighbouring agricultural land. Since the start of the programme, the Association reportedly has planted more than 2.9 million trees in Michoacán. The use of native species, such *Devoniana Lindley michoacana* and *Pseudostrobus Lindl*, has contributed to a reported survival rate of 85 percent of trees.

APEAM is also working with producers and local communities to preserve forests and improve the potential of ecosystem services that forests provide in the region. These include soil health preservation, water retention in forests, conservation of water bodies, and carbon sequestration.

4.13 Waste management

Climate risks addressed: the practice does not respond to specific climate hazards. Instead, waste management aims to reduce the industry's impact due to the production of residues and discarded material. This has important climate mitigation potential. Other benefits include economic gains through the commercialization of the by-products generated (e.g. biofertilizers, oil) and the reduction of production costs through the replacement of inputs.

The practice:

Industrialized avocado production waste has the potential to be used as a raw material for creating value-added products through processing. Avocado fruit and its by-products are rich sources of nutrients and phytochemicals that can be used in the food, pharmaceutical and cosmetic industries (Salazar-López *et al.*, 2021). Likewise, the waste generated by pruning old avocado trees can also be processed to create biofertilizers or used in the construction industry.

Table 10 lists some products that can be extracted from avocado residues.

Table 10. By-products derived from avocado residues (non-exhaustive)

By-product	Observations
Avocado oil	Avocado oil is extracted from ripe and mature avocado fruit, which have been found to have around 75 percent of the optimal available oil in the flesh. Oil is obtained from the pulp paste by grinding it and malaxing at 45–50 °C for 40–60 minutes. It is advised not to use overripe fruits, nor fruit with major postharvest disorders, such as pathogens, in order to obtain the highest oil quality. To minimize waste, companies can consider using low-category fruits considered as such due to their size or other organoleptic properties limiting their international or national market potential. It is important to note that avocado oil extraction is a mechanical extraction process, and an additional process is required to remove seeds/stones and peels or skins. Moreover, by using the flesh only, by-products like skin, rotten/overmatured fruit, pulp and seeds are generated.
Starch for the textile	Discarded avocado seeds can be used to extract starch and natural dye, as the starch content of an avocado seed can reach up to 74 percent of its dry weight, depending on the cultivar. These by-products can be used in textile applications, such as the utilization as a sizing agent, stiffening agent and as a fabric coloration thickener. The starch can also be used to produce warp yarn and be an eco-friendly and alternative option to the use of corn starch. The replacement of traditional warp yarn can also reduce pressure of on food production for the generation of these biomaterials by sustainable waste biomass. For the colouration of textiles, avocado seed contains orange-pink colour that can be applied to textile materials like silk, cotton and wool. The colours can be extracted through short and inexpensive processes.
Starch in the food industry	The starch produced can also be used in food products to provide texture and consistency in food formulations (e.g. desserts, puddings and frozen products).
Biopolymer in bioplastic	Starch biopolymer extracted from avocado seed can be used to create bioplastic. The material can constitute as a sustainable alternative and be used for different applications like packaging in food processing industries, agro-industries and paper industries.

By-product	Observations
Avocado powder	Peels and seeds can be dehydrated through spray drying technology and transformed into storable commodities. Aside from reducing waste, the practice can extend the shelf-life of high nutritious foods, with high antioxidant properties, such as avocado powders, which different food uses (e.g. food supplements, plant-based milk alternatives, seasoning).
Avocado tree wood chips or shavings	The wood chips and shavings can be used to produce compost, biofertilizers, compacted wood panels, among others. The use of wood derived from avocado tree pruning aims to avoid burning the wood in the open air and reduce greenhouse gas emissions (see **Figure 24**).

Source: see the list of references in the end matter.

Figure 24. Chips from pruned avocado trees for processing, minimizing burning of wood residues

© *APEAM, A.C.*

It is important to consider that many of these processes may require high investments for processing, as well as collaboration with other actors (e.g. government and research institutions) and stakeholders (e.g. biofuel or cosmetic industries). Also, their environmental and socioeconomic impact, carbon footprint and life cycle of the by-products generated should be assessed to ensure their sustainability (Hernández-Chaverri and Prado-Barragán, 2018).

4.14 Water-efficient irrigation systems

Climate risks addressed: drought, extreme heat, changing rainfall patterns, rainfall reduction, frosts. Other benefits include increased productivity due to reduced water and heat stress, water savings and thus, lower production costs associated with water and fuel/energy consumption for water abstraction (where applicable). In small-scale production settings, time dedicated for water collection and manual irrigation can be considerably reduced and allocated to other productive activities. This might be particularly beneficial for population groups that bear the responsibility for these tasks, including female smallholders.

The practice:

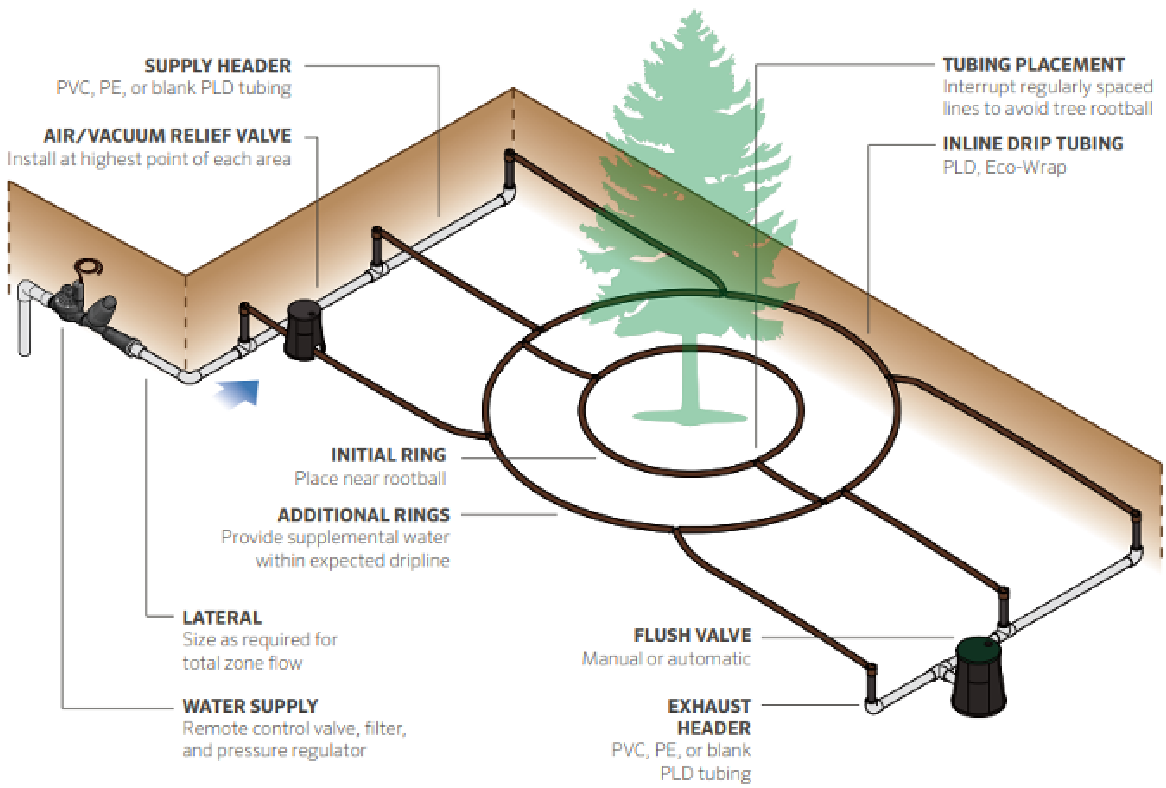
Plant-water relations play an important role in avocado tree cultivation, as avocado tree vegetative growth is very sensitive to water availability. Avocado production is favoured by a warm climate (up to 33 °C) and relative humidity of 60 to 65 percent (Kourgialas and Dokou, 2021). It has been observed that when water deficits occur in critical stages of fruit development, they can cause a reduction in fruit quality, such as smaller size or lower nutrient content (Lahav *et al.*, 2002). During flowering, water management is critical, as there is increased water demand during this period as the canopy increases. The growth phase of the fruit is the second crucial period for irrigation, as effective irrigation management can reduce early fruit drops and increase the fruit size (Schaffer *et al.*, 2013; Kourgialas and Dokou, 2021).

Although most of the avocado growing regions largely depend on rainfall for production, supplementary irrigation will increasingly be required to adapt to more recurrent drought events, rainfall variability, late onset of rainfall and water scarcity observed in most producing regions.

Drip irrigation is a water-efficient irrigation system that allows for the optimal use of water. The system delivers a controlled amount of low-pressure water through drippers working at a high application rate (Çetin and Akalp, 2019). The precision also limits evaporation and water runoff, while delivering the water at the root zone, where it is needed. As such, this technique promotes water consumption savings and is estimated to use up to 70 percent less water compared to conventional irrigation systems (e.g. flood irrigation) (UN Environment, 2015). The system generally consists of a water source, a pumping unit, a fertilization unit, filters, the distribution network and the drippers. For large trees, additional rings connected to the drip lines may need to be installed to provide enough water as seen in **Figure 25** (Hunter industries, n.d.).

Technical irrigation systems must be accompanied by water monitoring systems to ensure the optimal soil water content is reached to allow for optimal plant growth and effective irrigation management (Beyá-Marshall *et al*., 2022). In a study in Chile, the use of water monitoring sensors in avocado orchards led to water savings of 29 percent (ibid.). Beyond water use efficiency, close water monitoring will also enable producers to prevent potential water crisis due to overuse of water resources for irrigation. This may prevent potential ecological and economic damages, as well as social issues related to water access for the population and other industries.

Figure 25. Ring drip irrigation system



Source: **Hunter.** 2023. *Drip irrigation design and installation guide*. Cited 18 February 2023. Chwd.org/wp-content/uploads/Hunter-Drip-Irrigation-Design-Guide.pdf

Low-volume sprinklers are another water-efficient irrigation system that can allow for high water distribution uniformity and minimize soil over-wetting, which can spread root rot. A study of these systems in sandy soils in Morocco showed that sprinklers were more beneficial than drip irrigation, improving the quality and quantity of leaves and fruits (Ben Taleb, Brhadda and Ziri, 2022). The study suggests that the increase in the irrigated surface and the wetted volume could have played an important role in the stimulation of the physiological and metabolic activity of the tree and roots. Moreover, the use of sprinklers promoted an increase in yield by 35 percent, and lowered water use costs by 16 percent. Above canopy irrigation with sprinklers also demonstrated positive benefits in terms of protection of avocado trees against frost events (Remy *et al*., 2019). For more details see the section on **anti-frost measures**.

Other benefits of these irrigation methods are the increased efficiency in fertilizer use through the controlled application of nutrients with irrigation water, known as **fertigation**. The practice reduces the quantity of fertilizers used (estimated between 30 and 50 percent less fertilizer consumption; Fan *et al*., 2020) and promotes better management of the nutrients applied to the plant. In combination with water and wetting control, fertigation also prevents nutrient runoff. When properly done, fertigation can positively influence soil health, fruit quality and production costs. The water savings, and water and fertilizer use efficiency allow production to continue where and when less water (and nutrient additives) is available, leading to more stable and higher quality fruit production. However, the use of fertigation systems requires prior analysis of the chemical soil properties and mineral elements to identify the nutrient management approach needed. Overuse of fertilizers can lead to nutrient imbalances, which can harm soil microorganisms and reduce soil fertility over time. Additionally, fertigation can lead to increased soil salinity, which can reduce plant growth and limit the types of plants that can grow in the field if soil nutrient requirements are not correctly analysed.

Considerations for implementation of these systems include high investment costs of materials, filters and pumps, as well as the technical assistance required to ensure the systems are adequately implemented. Costs associated with fuel and energy needed to run the pumps should be factored in as this may make the costs of water abstraction and irrigation more expensive. Alternatives to fuel-based pumps could be considered depending on availability, cost and efficiency, including solar-powered water pumps to draw surface or ground water out for irrigation.

On the environmental side, **water abstraction requires close monitoring to avoid the potential depletion and contamination of groundwater resources due to salination and other processes**. It is also important to take into account the amount of water available in the production area when considering expanding the area for growing avocado. This would prevent producers from not being able to cover the irrigation needs of the new surface even with the use of technical irrigation. Likewise, this will mitigate the risks of depleting available water resources in a given location and detrimentally impacting ecosystems and communities.

It should also be noted that **irrigation by itself is not sufficient to increase production; it needs to be part of an integrated water resources management system to be successful**. Supplementary irrigation should be accompanied by complementary agronomic solutions linked to conservation agriculture, regenerative agriculture and other agroecological practices that preserve both water and soil resources. They may include nutrient management, **soil management practices**, and **integrated pest management**, among others.

Box 9 highlights how the widespread adoption of drip and micro-sprinkler irrigation has reduced water consumption in avocado plantations in Peru. The use of these systems by Westfalia Fruit is part of an integrated plan to manage water and soil.

Box 9. Use of water management practices through irrigation systems in Peruvian avocado production

Company or association: Westfalia Fruit
Region: Peru

One of the main areas for avocado production in Peru is in the highlands due to its long production season. The water for these higher altitude areas comes from glaciers, rainfall, lagoons and dams. However, in recent years, delays in the onset of rains have reduced the availability of water in critical months of fruit development. This has led to a decline in the volume of production and quality of the fruit. It also poses challenges for the distribution of the resource among the producers located in the mountain areas. The competition for water between producers in the same areas means that smaller producers who do not work with irrigation systems have greater problems to adequately distribute water in their fields.

To respond to this challenge, Westfalia Fruit has reported investing in the modernization of irrigation and the improvement of water management practices. Approximately 90 percent of its producers in the highland and coastal/lowland areas are using drip and micro-sprinkler irrigation for more efficient water use and also for better nutrient uptake through fertigation. At a company level, Westfalia Fruit constantly monitors the use of water by its producers which allows it to measure and regulate its consumption more efficiently.

These irrigation systems are being rolled out to all productive areas on the coastal and mountain areas to reduce the amount of water needed for production. The practice intends to increase productivity between 10 and 40 percent in comparison with flood irrigation or with technical irrigation where the design is not in accordance with the requirements of the crop.

Westfalia Fruit aims to reduce water consumption in its operations by 50 percent by 2023. The use of modernized irrigation systems is also promoting more efficient use of fertilizers, by assessing whether a reduction in fertilizer use can maintain good productivity.

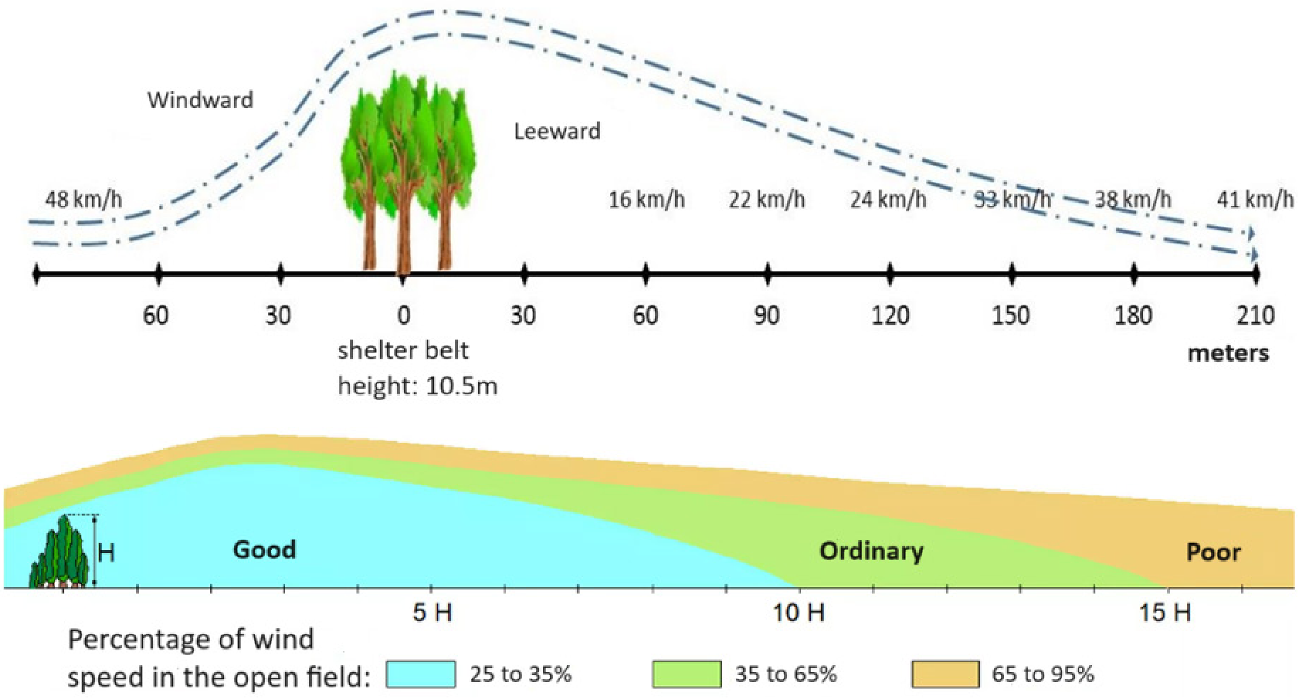
4.15 Windbreaks or living fences

Climate risks and impacts addressed: strong and frequent winds. Windbreaks have the potential to reduce the effects of **drought, extreme heat** and even **frost** as the planted trees also create a microclimate. Windbreaks also prevent **soil erosion** and offer protection to pollinators. By regulating microclimates, windbreaks may also help with the prevention of alternate bearing cycles.

The practice:

Windbreaks are formed by one or more rows of trees and shrubs of different heights (short, medium and tall), which are placed opposite to the wind direction. They are an important tool in the implementation of climate-smart agriculture and agroecology strategies. The aim is to reduce the force and speed of the wind, and the impact that these cause on avocado trees. The protection offered by windbreaks is particularly important during the flowering and fruit setting phases, as it prevents flowers and small fruits from falling, flowers drying, branches breaking, and reduction of pollination activity associated with strong wind (Holmes and Farrell, 1993). Windbreaks also contribute to limiting wind erosion and regulating climate conditions in the production area (Singh, 2023). The reduction of strong wind could also be reflected in improved fruit quality due to the lower incidence of wind scarring and thus a reduction of the potential for pathogens that can enter the fruits through these scars (Holmes and Farrell, 1993). **Figure 26** shows how windbreaks work.

Figure 26. Effect of the forest curtain on reduction of wind speed (top) and protection effectiveness with respect to the height (H) of the curtain (bottom)



Source: **Oberschelp, J., Harrand, L., Mastrandrea, C., Salto, C., & Florez, M.** 2020. *Cortinas forestales: rompevientos y amortiguadoras de deriva de agroquímicos*. EEA Concordia. Instituto Nacional de Tecnología Agropecuaria. Ediciones INTA. Buenos Aires.

In avocado production, windbreaks are particularly suitable in areas with low precipitation, as the presence of trees and shrubs help to preserve the humidity and moderate temperature in the plots. The practice also provides other ecosystem services such as landscape improvement or restoration, pollination protection and biological corridors for insects and animals (Weninger *et al.*, 2021), particularly when native and local species are used. Windbreaks can also be used as living fences to define the boundaries of fields. The implementation of this adaptation measure also supports climate mitigation efforts, as the increased biomass present in the production system can promote carbon sequestration and storage.

The establishment of living fences adjacent to a stream, lake, wetland, as well as the productive area, can also act as **forest buffers**. Forest buffers provide food and cover for wildlife, improve water availability, regulate water and environmental temperatures and slows out-of-bank flood flows. Thus, acting as natural shelters for local biodiversity and as a line of defence against extreme weather events. To learn more about forests and forest management, see section on **sustainable forest management**.

Box 10 provides an example of how windbreaks have been implemented in Mexican avocado orchards with positive environmental outcomes.

Box 10. Implementation of windbreaks to reduce the impacts of strong winds on avocado production in Mexico

Company or association: APEAJAL
Region: Mexico

Since 2018, APEAJAL has implemented a reforestation programme with native trees around the productive area to act as windbreaks and live fences, reducing wind speed, and thus the impact on production. By 2022, 217 300 trees had been planted in a total of 263 production units, located in the 23 municipalities of Jalisco where the largest number of avocado orchards are concentrated.

The strategy has reportedly had other benefits such as the preservation of soil moisture and temperature control in production areas. In addition, producers have included plants that attract pollinators, promoting the preservation of their population and increasing their presence within production areas. The measures taken by the Association are included as part of a program that in the medium term aim to reduce the impacts caused by extreme weather events such as strong winds, hailstorms, and rising temperatures.

Considerations for implementation include the selection of tree and shrub species that do not imply high competition with avocado orchards (Taleb *et al*., 2018). It is recommended that the selected species are fast and upright growing, with perennial foliage and are not known hosts to avocado pests and diseases. Tree and shrub species should also be flexible and respond well to pruning. In tropical climates, rose apple (*Eugenia malaccensis*), olive (*Simarouba glauca*), poppy (*Hibiscus sepium*), itabo (Yucca elephantipes), glossy privet (*Ligustrum lucidum*), among others could be used as windbreaks (Garbanzo, 2015). In Mediterranean climates, horizontal cypress (*Cupressus horizontalis*) and Arizona cypress (*Cupressus arizonica*) are some recommended species (Taleb *et al*., 2018).

It is advised that native species are incorporated as part of windbreaks to protect local biodiversity and ecosystems and prevent the risk of invasion from non-native species. Assessing soil properties and water availability is critical to ensure the maximum survival and performance of planted species.

Chapter 5.
Discussion and conclusions

Adaptation to climate change is required to ensure the continuity of global avocado production and trade. Adapting to climate change will enable companies and producer associations to protect their production systems and care for their environment and workers, while minimizing the creation of new risks associated with increasing GHG emissions and global warming. Climate adaptation will thus contribute to the resilience and sustainability of agricultural value chains.

Although climate change and its associated impacts will be felt differently both across and within producing countries and regions, **extreme weather events will increase in frequency and intensity**. Moreover, it is expected that **multiple climate risk factors will occur concurrently** in the same regions, which in combination with other non-climatic factors such as economic slowdown or pandemics, will increase the overall risk to agricultural production systems. As such, avocado producers need to be prepared to deal with multiple risks in a synchronized manner, so that they can maximize the benefits from synergies associated with combining adaptation practices. This approach will also help to minimize the risk of natural systems reaching adaptation limits – a key risk factor identified in the IPCC report in the face of ongoing increases in global warming (IPCC, 2023).

Knowledge and information on how to adapt to climate change in the avocado sectors already exist, and many companies and producer associations are taking a proactive role in designing strategies and testing practices in the field to deal with climate change and extreme weather events. Chapter 4 of this guide highlights some of the existing technologies, practices, techniques and systems that can help producers to deal with ongoing changes and to prepare for and prevent future adverse climate impacts. Examples of good adaptation practices from companies and associations are also featured.

Many of the adaptation practices identified are likely to be relevant for all tropical fruit production systems (e.g. drainage systems, early warning systems, integrated pest management, integrated water management, mulching and cover crops, waste management, wind breaks and living fences), while other practices identified are specific to the adaptation needs of avocado (e.g. agroforestry, anti-frost systems, protection of pollinators and beekeeping, shade nets and sustainable forest management).

The selected **adaptation practices address multiple climate risks and associated impacts simultaneously**. This is important to highlight, as discrete adaptation strategies that deal with only one risk factor at a time are less likely to achieve the desired impact in the way that combining many practices will.

Climate adaptation is a continuous process that takes time and requires investments in information and data. Regular data and information updates on production factors and climate trends are needed in order for adaptation practices to stay relevant. Companies and producer associations may consider developing adaptation strategies that take into account short-, mid- and long-term projected climate trends. They also need to bear in mind that some practices might become obsolete as global and local temperatures and precipitation patterns change. This may require them to continually invest, explore and adopt new approaches to transform their production systems to ensure fruit supply in the longer term. A detailed assessment of the expected climate risks and impacts in each producing region and localities might be necessary to make the adaptation strategy as responsive as possible. The collection of climate data both on farm and by public institutions in localized areas is needed to support this process. Capacity building support for producers on how to interpret this data and incorporate this information into their decision-making processes is also required.

Adaptation and mitigation efforts to reduce greenhouse gas emissions should go hand-in-hand whenever possible. Adopting adaptation practices that have climate mitigation potential will help to not only reduce GHG emissions but may also potentially extend the shelf-life of available adaptation practices. Likewise, mitigation strategies can also be designed in a way to contribute to and reinforce adaptation. Some of the adaptation practices identified for avocado production such as sustainable soil management, agroforestry, sustainable forest management, waste reduction and management, also have positive effects on reducing greenhouse gas emissions in the production sector. These practices also have important implications in storing carbon, for instance through improved soil health or increased biomass, making avocado production more sustainable.

The adoption of adaptation technologies and practices requires some key considerations:

- **Damage allowance:** Some level of fruit loss/damage may be unavoidable in adaptation, especially during the early stages of introducing the practice. For example, when implementing integrated pest and weed management practices, producers may need to tolerate the presence of a minimum number of pests, diseases and weeds to allow for a natural re-balancing of the ecosystems. Also, phasing out synthetic fertilizers may mean a reduction in yield in initial phases as the soil properties and structures are restored. The level of damage farmers and companies are willing to assume will depend on their own income and adaptation needs, and the long or short-term vision guiding the management of the operation.

- **Investment costs:** Producers, associations and companies need to assess the investments required to integrate new technologies or techniques into the production system as well as the benefits, including environmental and social benefits. These may include costs associated with losses and damage of production and infrastructure, and health risks among others, if no action is taken. A cost–benefit analysis might be needed to assess the advantages and costs the companies would incur in a business-as-usual scenario versus a scenario where the adaptation strategies are implemented.
- **Time requirements:** The development of some adaptation practices may take longer than others, thus requiring a longer time horizon and greater investment to move from concept to implementation. Some of these adaptation solutions include the development of climate-resilient seeds, plants and genetic material, as well as the configuration of early warning systems.

All adaptation practices should aim to take into account all three dimensions of sustainability. While the environmental dimension is the clear entry point to promote adaptation in the tropical fruit sector, addressing social risks (e.g. health of workers) and economic risks (e.g. increased costs to maintain infrastructure) associated with climate change impacts is also crucial to the long-term sustainability of business operations.

To date, there is **limited evidence on the social impact of climate change** on the livelihoods, health and safety of producers and workers operating in avocado value chains. However, some research points at the high vulnerability that workers face in agrifood value chains, particularly field workers, due to extreme weather events. This is linked to the strenuous nature of the work that is performed primarily outdoors, usually under inadequate working conditions (El Khayat *et al*. 2022). Some avocado producing companies in Colombia have already noted these risks, especially those related to **heat stress and associated illnesses** derived from increasing temperatures and solar radiation.

The country risk profiles developed by the World Bank indicate that an increase in the frequency of heat waves and resultant heat stress on workers will become more prevalent in coming years, particularly in producing countries such as Colombia, Kenya, and South Africa, with associated loss of labour productivity and risk to human life (World Bank, 2021). Heat stress is known to increase mortality and morbidity for the most vulnerable, especially the elderly, children and pregnant women. Additionally, children's learning ability significantly decreases with increased heat exposure. Other projected health stressors associated with climate change and identified across many of the countries included in the guide, include an increase in air pollution, asthma, vector-borne diseases (i.e. malaria, dengue, schistosomiasis, and tick-borne diseases), water-borne and food-borne diseases, and diarrheal diseases. Further efforts are required across all countries and sectors to better understand the impact of climate variability on human health and integrate strategies to deal with climate sensitive health issues into existing health programs and policies. Awareness raising and cross-ministerial dialogue will also be required to ensure that these issues are adequately reflected in other sectoral policies dealing with climate change, including the NAP-Ag plans, as the impact of climate change on human health will affect productivity in the agriculture sector and others.

The extent of impacts of climate change and the coping strategies available to the various segments of the population depends heavily on their socioeconomic status, sociocultural norms, access to resources, poverty as well as **gender and age** (FAO, 2018b; 2019b). **Women and youth are among the highest risk groups when it comes to climate change impacts**, yet no research could be found on specific impacts of climate change on women and youth vis-à-vis engagement in global avocado value chains. This despite the important role women play in the harvesting and packing of this commodity. Gender-disaggregated research is urgently required to better understand the key factors that account for the differences between women's and men's vulnerability to climate change risks, and how to build tailored adaptation strategies to address these.

Other studies have shown that violence, including physical, psychological, and reproductive violence against women, is more pronounced after disasters triggered by natural hazards, with other consequences on women's wellbeing (Sloand *et al*., 2015). Women and girls face increased risks of gender-based violence following a climate or other unexpected shocks (e.g. COVID-19 outbreak) (Sloand *et al*., 2015). For example, shocks tend to intensify domestic and social tensions due to increased unemployment, higher economic dependence of women on the breadwinning partner and shortages of basic services (e.g. food, water, roads). Gender-based violence has been an issue widely noted in other export-oriented agrifood value chains, including banana, grapes and vegetables (EBRD and CDC, 2019), suggesting that it could also be a concern in the avocado sector.

As discussed throughout the guide, climate change will influence food production via direct and indirect effects on crop growth processes, which has **implications for food security and nutrition**. The breakdown in food systems due to higher temperatures, land and water scarcity, flooding, drought and displacement, will negatively impact agricultural production and disproportionally affect the most vulnerable people, who are already face hunger and food insecurity. Vulnerable groups risk further deterioration of available food and nutrition when exposed to extreme climate events. Avocados form part of a healthy diet and are an important source of vitamins and nutrients for consumers in both the producing and importing countries. On this basis, avocado companies could consider how they may be able to support vulnerable populations in their local communities through targeted social outreach programmes that aim to improve food security and nutrition such as public procurement (e.g. school feeding programmes, community canteen services) or food banks.

The Responsible Fruits Project recognizes that **enhancing the adaptive capacity and climate resilience of the avocado value chain cannot be achieved through a single-actor approach**. The complex challenges associated with climate change impacts are best solved through the cooperation of stakeholder groups including governments, companies, producer organizations, research and training institutes, worker unions, and other civil society organizations. Establishing mechanisms for multistakeholder collaboration may be the most effective approach to tackle the impacts of global warming on the avocado industry in the future. Current adaptation solutions highlighted in this guide and existing gaps in knowledge (e.g. plant breeding and early warning systems) demonstrate that efforts are needed across the industry in all producing countries to engage with other stakeholders. These include research institutions and relevant ministries to increase the availability of sustainable climate adaptation solutions identified through research and development, and to promote widespread adoption through government incentives and policy dialogue. The adoption of adaptation practices not only requires the development of new technologies, but also technical assistance (e.g. through extension services and targeted capacity development programmes), information exchange (e.g. climate data and alerts, information on emerging pathogens, etc.) and available financing/incentives for the uptake of new, and potentially risky, technologies and practices.

At an institutional and policy level, FAO's work to support countries to integrate adaptation solutions specifically for the agriculture sector as part of the broader National Adaptation Plans developed by countries in line with their NDC commitments is an essential step. While the NAP-Ag plans developed for the two countries included in this guide (i.e. Colombia and Kenya) do not focus specifically on the tropical fruit sector, many of the adaptation measures proposed are relevant for tropical fruit production and have been discussed in **Chapter 4** of the guide (e.g. water management, soil conservation, protection of biodiversity, agroforestry, early warning systems). **Understanding how specific commodity sectors like avocado production and export can contribute towards the achievement of mitigation and adaptation targets set out in the NDCs and NAPs is useful.** Improved understanding may help the industry to align their efforts with those at a national and sub-regional level and demonstrate to policy makers that collective efforts are being made by industry in support of these plans. Efforts to generate evidence of the impacts of implementing adaptation practices through better monitoring and evaluation is also needed to further advance these claims.

The Responsible Fruits Project is committed to supporting avocado producers and exporters globally to deal with climate change and other identified sustainability risks through the generation of practical tools. The project has been working on different technical materials and tools tailored to the avocado industry, and some applicable to the wider tropical fruit sector. These products are discussed below.

The gap analysis guide helps companies to compare the standards and policies they use with the OECD-FAO Guidance for Responsible Agricultural Supply Chains, the global benchmark for due diligence and responsible business conduct in the agriculture sector. By using the gap analysis tool, companies can assess and identify how their operations are impacting the ecosystems in which they operate and identify any negative influence they may be having on the environment and climate (among other factors). By identifying these risks and learning how to manage them, companies can improve their business performance, increase sustainability, and strengthen resilience to external shocks, including climate risks. In many countries, newly passed or proposed laws require companies to carry out risk-based due diligence to identify, assess, mitigate, prevent, and account for how they address actual and potential adverse impacts of their activities and those of their suppliers and business partners. These include areas related to use of agrochemicals and natural resources management, both with direct impacts on climate adaptation and mitigation.

The project's ongoing work to develop a carbon and water footprint measurement tool for the pineapple industry also contributes to this goal. A similar tool could be developed for the avocado industry if there is sufficient interest and resources.

The project has also carried out a series of technical webinars addressing some of the most pressing climate challenges to the avocado sector. These include deforestation prevention, use of agrochemicals and maximum residues limits, water monitoring and use, climate change adaptation, biodiversity protection, reduction of loss and waste and soil health and land degradation.

In addition, the project conducted a detailed study to understand the resilience challenges the avocado sector is facing. Climate change and variability feature prominently as a key resilience challenge facing the industry. Based on the results from this study, the project will elaborate a technical guide, technical briefs and capacity development activities to address areas that directly and indirectly support companies' efforts to adapt and transform vis-à-vis future extreme weather events and a changing climate. The technical guide will focus on supporting businesses and associations in the avocado industry to better track and report on their progress towards resilience and sustainability.

In conclusion, this guide was produced by the Responsible Fruits Project for producers and exporters of avocado who are interested in learning more about climate change in the context of their own business systems and how they can adapt to the effects of climate change. It is hoped that for many the guide will be the starting point for discussion on national, regional and localized climate change impacts on avocado production and stimulate joint planning for research on adaptation solutions to support the long-term sustainability of the export industry. The limitations of the guide were acknowledged in **Chapter 1**, given the lack of time and resources to conduct the field-based, longitudinal scientific research that is needed to answer specific questions related to climate change impacts over time for avocado under various production conditions. Indeed, more longitudinal research that is commodity and location-specific is needed to better understand climate risks and long-term effects on tropical fruit crops and identify innovative adaptation solutions.

Annex 1

Suggested resources

The lists below provide additional reference material, such as websites, technical publications and guidance materials, policy briefs, etc. that can support producers, associations and companies to learn more about climate change, its impacts on the tropical fruit sector and adaptation options available. Some toolboxes are also suggested that may help stakeholders in the avocado industry to define their adaptation goals and track progress towards these.

Technical and guidance publications and articles

Avocado

Alliance of Bioversity International & CIAT. 2020. *Concept Note Development of Climate Risk Profiles for Agricultural Commercialization Clusters (ACC)*. Rome, Alliance Biodiversity & CIAT. [Cited 16 June 2023] https://alliancebioversityciat.org/publications-data/concept-note-development-climate-risk-profiles-agricultural-commercialization

Avila-Campos, J. & Buitrago, L. 2020. *Sistemas agropecuarios sostenibles, biodiversidad y servicios ecosistémicos: Aguacate*. WCS (Web Coverage Service). https://www.researchgate.net/publication/349640678_Sistemas_agropecuarios_sostenibles_biodiversidad_y_servicios_ecosistemicos_Aguacate

Castillo, N. & Van Zonneveld, M. 2015. *Potencial ecológico de frutales nativos del neotrópico, aguacate y anonas, en la diversificación de los paisajes cafetales en América Central como estrategia de adaptación al Cambio Climático: Informe Técnico*. Copenhague, Programa de investigación de CGIAR en Cambio Climático, Agricultura y Seguridad Alimentaria (CCAFS). [Cited 16 June 2023]. https://alliancebioversityciat.org/publications-data/potencial-ecologico-de-frutales-nativos-del-neotropico-aguacate-y-anonas-en-la

Díaz Ramírez, L., Hurtado, J., Charry, A. & Jäger, M. 2021. *Brechas tecnológicas de la cadena productiva del aguacate Hass en el Valle del Cauca y descripción del estado del arte*. Universidad Nacional de Colombia. https://repositorio.unal.edu.co/handle/unal/80835 (Spanish only)

Díaz Ramírez, L., García Botina, M., Jäger, M. & Hurtado, J. 2021. *Plan de investigación y desarrollo de la cadena productiva del aguacate Hass en el Valle del Cauca a partir de sus principales brechas tecnológicas*. Universidad Nacional de Colombia. https://repositorio.unal.edu.co/handle/unal/80858 (Spanish only)

Fontagro. 2016. Fruit Productivity and Competitiveness Andean. United States of America. [Cited 16 June 2023]. https://www.fontagro.org/new/proyectos/productividad-y-competitividad-fruticola-andina/en

Jinés León, A. & Eitzinger, A. 2021. *Identificación de las zonas de ladera aptas para el cultivo de aguacate Hass en el territorio del Valle del Cauca*. Universidad Nacional de Colombia. https://repositorio.unal.edu.co/handle/unal/80866 (Spanish only)

Martínez, E., Moreno-Ortega, G. & Pliego, C. 2021. Manejo sostenible del riego en el cultivo de aguacate. Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción Ecológica. [Cited 16 June 2023]. https://www.juntadeandalucia.es/agriculturaypesca/ifapa/servifapa/registro-servifapa/32ee03ab-2ea6-489b-926f-0bb126945700

Rainforest Alliance. 2022. Aguacates más sostenibles para mercados más responsables. *Rainforest Alliance*, 6 May 2022. United States of America. [Cited 16 June 2023]. https://www.rainforest-alliance.org/es/perspectivas/aguacates-sostenibles-mercados-responsables/

Ruiz, A. 2020. Efficient and sustainable cultivation of avocado with the Ecoculture programme. *Ecoculture*, 8 June 2020. Almeria, Spain. [Cited 16 June 2023]. https://ecoculturebs.com/en/2020/07/28/cultivo-eficiente-y-sostenible-de-aguacate-con-el-programa-ecoculture-2/

USAID. 2019. *Avocado production manual (Persea Americana L.)*. Feed for the Future Tanzania. https://fintracu.fintrac.com/sites/default/files/tech_manuals/Fintrac%20U_Avocado%20Production%20Manual.pdf

Production sector in general

FAO. 2023. *SEPAL (System for earth observation data access, processing and analysis for land monitoring)*. Rome. www.fao.org/3/cb2876en/cb2876en.pdf

Global Nature Fund. 2023. Biodiversity check agrícola. German Agency for International Cooperation (GIZ). Germany. www.delcampoalplato.com/en/home-engl/biodiversity-check-agricola-engl

Miles, L., Agra, R., Sengupta, S., Vidal, A. & Dickson, B. 2021. Nature-based solutions for climate change mitigation. IUCN and UN Environment Programme. www.unep.org/resources/report/nature-based-solutions-climate-change-mitigation

Pronaturaleza – Fundación Peruana por la Conservación de la Naturaleza. 2021. *Biodiversity hotspot of the tropical Andes*. Perú, Critical Ecosystem Partnership Fund. www.cepf.net/sites/default/files/tropical-andes-ecosystem-profile-2021-spanish.pdf

United Nations Environment Programme. 2015. Microfinance for ecosystem-based adaptation measures – Options, costs and benefits. Panama. www.unep.org/resources/publication/microfinance-ecosystem-based-adaptation-options-costs-and-benefits

Toolboxes and websites

CABI. 2023. CABI Digital library - Research and learning in agriculture, the environment and the applied life sciences. [Cited 15 March 2023]. https://www.cabidigitallibrary.org

CEPF (Critical Ecosystem Partnership Fund). 2023. Explore the Biodiversity Hotspots. In: *Critical Ecosystem Partnership Fund*, Protecting biodiversity by empowering people. [Cited 16 June 2023]. https://www.cepf.net/node/1996 FAO 2023. Climate Risk Toolbox. In: *FAO*. [Cited 19 June 2023]. https://data.apps.fao.org/crtb/

FAO. 2023. Analysis of Vulnerability and Risk due to Climate Change in the Agriculture sector. Colombia. In: *FAO Colombia*. [Cited 16 June 2023] https://cambioclimatico.fao.org.co

FAO. 2023. Climate Change Knowledge Hub In: *FAO Climate Change*. [Cited 16 June 2023]. https://www.fao.org/climate-change/knowledge-hub

FAO. 2023. Global soil partnership. In: *FAO*. Rome. [Cited 16 June 2023]. https://www.fao.org/global-soil-partnership/en/

FAO. 2023. Soil and water conservation in Latin America and the Caribbean. In: *FAO*. Rome. [Cited 16 June 2023]. https://www.fao.org/americas/prioridades/suelo-agua/en/

FAO. 2023. SEPAL Forest and Land Monitoring for Climate Action. In: *FAO*. Rome. [Cited 19 June 2023]. https://www.fao.org/in-action/sepal/overview/en

GreenFacts. 2022. Biodiversity A Global Outlook. In: *GreenFacts, Facts on Health and the Environment*. [Cited 16 June 2023] https://www.greenfacts.org/en/global-biodiversity-outlook/links/index.htm

GreenFacts. 2022. Themes. In: *GreenFacts, Facts on Health and the Environment*. [Cited 16 June 2023]. https://www.greenfacts.org/en/digests/themesindex.htm

GBIF (Global Biodiversity Information Facility). 2023. Free and open access to biodiversity data. Copenhagen, GBIF Secretariat. [Cited 16 June 2023]. https://www.gbif.org

International Model Forest Network. 2019. *Model Forest Toolkit - A how to manual*. Ottawa, Canada. https://imfn.net/wp-content/uploads/2019/03/Toolkit2019_Eng_All-in-One_FINAL.pdf

International Union for Conservation of Nature. 2023. Contributions for Nature Platform. [Cited 19 June 2023]. https://www.iucn.org/resources/conservation-tool/contributions-nature-platform

Open Foris. 2023. Free open-source solutions for environmental monitoring. https://openforis.org/

UNEP (United Nations Environmental Programme). 2023. Climate Adaptation Project List. In: *UNEP, Climate Adaptation*. [Cited 16 June 2023]. https://www.unep.org/explore-topics/climate-action/what-we-do/climate-adaptation/climate-adaptation-project-list

WeADAPT. 2023. Climate change adaptation planning, research and practice – a collaborative platform on climate change adaptation issues. [Cited 18 August 2023]. https://www.weadapt.org/

World Bank. 2022. Climate Change Knowledge Portal for development practitioners and policymakers. In: World Bank Group [online]. Washington. [Cited 7 October 2022]. https://climateknowledgeportal.worldbank.org

WFP (World Food Programme). 2023. WFP Dataviz - Vulnerability Assessment Monitoring (VAM). https://dataviz.vam.wfp.org

Policy briefs and full publications

FAO and UNDP. 2023. Private sector mapping, outreach, and engagement in climate responsive agrifood systems - SCALA private sector engagement guidance series. March 2023. Rome. https://doi.org/10.4060/cc4689en

GIZ. 2021. *Climate change and its effects on banana production – Colombia, Costa Rica, the Dominican Republic and Ecuador*. www.nachhaltige-agrarlieferketten.org/fileadmin/user_upload/Climate_change_and_its_effects_on_banana_production_English__1_.pdf

Hallegatte, S., Rentschler, J. & Rozenberg, J. 2020. Adaptation Principles: A Guide for Designing Strategies for Climate Change Adaptation and Resilience. World Bank, Washington, DC. http://hdl.handle.net/10986/34780

Parker, L.., Bourgoin, C., Martinez-Valle, A. & Läderach, P. 2019. *Vulnerability of the agriculture sector to climate change: The development of a pan-tropical Climate Risk Vulnerability Assessment to inform sub-national decision making*. PLoS ONE 14(3): e0213641. Australia, University of Southern Queensland. https://doi.org/10.1371/journal.pone.0213641

World Bank. 2022. Country risk profile reports. Rome. [Cited 3 February 2023]. https://datacatalog.worldbank.org/search/dataset/0041074

References

Acosta-Rangel, A., Li, R., Mauk, P., Santiago, L. & Lovatt, C. 2021. Effects of temperature, soil moisture and light intensity on the temporal pattern of floral gene expression and flowering of avocado buds (*Persea americana cv. Hass*). *Scientia Horticulturae*.

Alon, E., Shapira, O., Azoulay-Shemer, T. & Rubinovich, L. 2022. Shading nets reduce canopy temperature and improve photosynthetic performance in 'Pinkerton' avocado trees during extreme heat events. *Agronomy*, 12(6): 1360. https://doi.org/10.3390/agronomy12061360

Altieri, M., Fonseca, J., Caballero, J. & Hernandez, J. 2006. Manejo del agua y restauración productiva en la región indígena Mixteca de Puebla y Oaxaca.

Altieri, M.A. & Nicholls, C.I. 2004. An agroecological basis for designing diversified cropping systems in the tropics. *Journal of Crop Improvement*, 11(1-2): 81–103. https://doi.org/10.1300/J411v11n01_05.

Álvarez-Bravo, A., Salazar-García, S., Ruiz-Corral, J.A. & Medina-García, G. 2017. Scenarios of how climate change will modify the 'Hass' avocado producing areas in Michoacán. *Revista Mexicana de Ciencias Agrícolas*, 8 (19): 4035–4048.

Anguiano, C.J., Alcántar., R.J., Toledo, B.R., Tapia, L.M. & Vidales-Fernández, J.A. 2007. Soil and climate characterization of the avocado-producing area of Michoacán, Mexico. Proceedings VI World Avocado Congress. http://avocadosource.com/wac6/en/Extenso/3c-112.pdf

Arpaia, M., Collin, S., Sievert, J. & Obenland, D. 2018. 'Hass' avocado quality as influenced by temperature and ethylene prior to and during final ripening, Postharvest Biology and Technology. https://doi.org/10.1016/j.postharvbio.2018.02.015

Armenta-Bojórquez, A.D., García-Gutiérrez, C., Camacho-Báez, J.R., Apodaca-Sánchez, M.Á., Gerardo-Montoya, L. & Nava-Pérez, E. 2010. Biofertilizantes en el desarrollo agrícola de México. *Ra Ximhai*, 6(1): 51–56. [Biofertilizers in the Mexican agriculture development].

Assouline, S., Hochberg, U. & Silber, A. 2021. The impact of tree phenology on the response of irrigated avocado: the hysteretic nature of the maximum trunk daily shrinkage. *Agricultural Water Management*, 256. https://doi.org/10.1016/j.agwat.2021.107104. https://www.sciencedirect.com/science/article/pii/S0378377421003693.

Barra, P., Inostroza, N., Mora, M.L., Crowley, D. & Jorquera, M. 2017. Bacterial consortia inoculation mitigates the water shortage and salt stress in an avocado (*Persea americana Mill.*) nursery. *Applied Soil Ecology*, 111: 39–47. https://doi.org/10.1016/j.apsoil.2016.11.012

Bar-Noy, Y., Sofer-Arad, C., Perel, M., Cohen, H., Senesh, N., Noy, M. & Rubinovich, L. 2019. Frost protection efficiency evaluation in avocado with a horizontal wind machine. *Fruits, The International Journal of Tropical and Subtropical Horticulture*, 74(3): 124–129.

Ben Taleb, H.N.B., Rabea, Z., Farré, J.M & Gmira, N. 2018. Comparison of the technical management of avocado trees between Morocco and Spain. https://core.ac.uk/download/pdf/234662747.pdf

Bergh, B. 1976. Avocado breeding and selection. *Proceedings of the First International Tropical Fruit Short Course: The Avocado, University of Florida:* 24–33.

Bessert, L. 2022. Keyline Design- water management of agricultural landscapes: Key for Regenerative agriculture? University of Kassel. https://agroforst-info.de/wp-content/uploads/2023/01/bessert-Keyline_angepasst.pdf.

Beyer, C.P., Cuneo, I.F., Alvaro, J.E. & Pedreschi, R. 2021. Evaluation of aerial and root plant growth behavior, water and nutrient use efficiency and carbohydrate dynamics for Hass avocado grown in a soilless and protected growing system. *Scientia Horticulturae*, 277: N.PAG-N.PAG. https://doi.org/10.1016/j.scienta.2020.109830.

Bhattacharjee, P., Warang, O., Das, Sh. & Das, S. 2022. Impact of climate change on fruit crops- A review. *Current World Environment*. 17 (2). India. 319–330 p. http://dx.doi.org/10.12944/CWE.17.2.4

Biazin, B., Haileslassie, A., Zewdie, T., Mekasha, Y., Gebremedhin, B., Fekadu, A. & Shewage, T. 2018. Smallholders' avocado production systems and tree productivity in the southern highlands of Ethiopia. *Agroforestry Systems*, 92(1): 127–137. https://doi.org/10.1007/s10457-016-0020-2

Brookes, G. 2022. Genetically Modified (GM) Crop Use 1996–2020: Impacts on Carbon Emissions. *GM Crops and Food*, 13(1): 242–261.

Buxton, M.N., Hoare, R.J.B., Broussard, M.A., Van Noort, T., Fale, G.R.T., Tamatea, N. & Pattemore, D. 2023. Moths as potential pollinators in avocado (*Persea americana*) orchards in temperate regions. *New Zealand Journal of Crop and Horticultural Science*, 51:1, 27–38. https://doi.org/10.1080/01140671.2021.1966480.

Caldana, N.F.d.S., Nitsche, P., Martelócio, A., Rudke, A., Zaro, G., Batista Ferreira, L., Contador Zaccheo, P., Colucci de Carvalho, S. & Martins, J. 2019. Agroclimatic risk zoning of avocado (*Persea americana*) in the hydrographic basin of Paraná River III, Brazil. *Agriculture*, 9(12). https://doi.org/10.3390/agriculture9120263.

University of California. 2023. *Avocado Handbook*. https://ceventura.ucanr.edu/Com_Ag/Subtropical/Avocado_Handbook/Frost_Control_Freeze_Damage_/Protecting_Avocados_from_Frost_/

Cañas-Gutiérrez, G.P., Sepulveda-Ortega, S., López-Hernández, F., Navas-Arboleda, A.A. & Cortés, A.J. 2022. Inheritance of yield components and morphological traits in avocado cv. Hass from "Criollo" "Elite Trees" via half-sib seedling rootstocks. *Frontiers in Plant Science*, 13. https://doi.org/10.3389/fpls.2022.843099.

Castro Acosta, E.G., Aviles, A., Mendoza, C., López, A. & Secundino, K. 2022. Cambio climático y producción de aguacate. https://www.researchgate.net/publication/357662730_Cambio_climatico_y_produccion_de_aguacate.

Çetin, Ö. & Akalp, E. 2019. Efficient use of water and fertilizers in irrigated agriculture: drip irrigation and fertigation. *Acta Horticulturae et Regiotecturae*, 22(2): 97–102.

Chaddad, F. 2016. Chapter 2 - Enabling Conditions. In: F. Chaddad, ed. *The Economics and Organization of Brazilian Agriculture*, pp. 19-44. San Diego, Academic Press.

Chairani, S., Megawati, S., Novpriansyah, H., Banuwa, I.S. & Buchari, H. 2018. Tracking the fate of organic matter residue using soil dispersion ratio under intensive farming in red acid soil of Lampung, Indonesia.

Charre-Medellin, J.F., Mas, J.-F. & Chang-Martinez, L.A. 2021. Potential expansion of Hass avocado cultivation under climate change scenarios threatens Mexican mountain ecosystems. *Crop & pasture science*. https://doi.org/10.1071/CP20458.

Chawla, R., Sheokand, A., Rai, M. R., and Kumar, R. 2021. Impact of climate change on fruit production and various approaches to mitigate these impacts. *The Pharma Innovation Journal*. 10(3): 564–571.

Chernoivanov, S., Neuberger, I., Levy, S., Szenes, N. & Rubinovich, L. 2022. Covering young Reed avocado trees with shading nets during winter alleviates cold stress and promotes vegetative growth. *Eur.J.Hortic.Sci.*, 87(1): 1–10. https://doi/org/10.17660/eJHS.2022/007

Chung, S., Rho, H., Lim, C., Jeon, M., Kim, S., Jang, Y. & An, H. 2022. Photosynthetic response and antioxidative activity of 'Hass' avocado cultivar treated with short-term low temperature. *Scientific Report*, 12: 11593.

Consejo Civil Mexicano para la Silvicultura Sostenible, AC. 2010. *El manejo forestal sostenible como estrategia de combate al Cambio Climático: las comunidades nos muestran el camino*. México.

Crane, J.H., Wasielewski, J., Carrillo, D., Gazis, R., Schaffer, B., Ballen, F., Evans, E. & Regalado, R. 2020. Recomendaciones para la detección y mitigación de la marchitez del laurel en árboles de aguacates y especies relacionadas en jardines y patios hogareños. HS1358s/HS1384, 9/2020. EDIS, 2020(5).

Crumpler, K., Abi Khalil, R., Tanganelli, E., Rai, N., Roffredi, L., Meybeck, A., Umulisa, V., Wolf, J. and Bernoux, M. 2021. (Interim) *Global update report – Agriculture, Forestry and Fisheries in the nationally determined contributions*. Environment and Natural Resources Management Working Paper No. 91. Rome, FAO. https://doi.org/10.4060/cb7442en

del Carmen Ponce-Rodríguez, M., Carrete-Carreón, F.O., Núñez-Fernández, G.A., de Jesús Muñoz-Ramos, J. & Pérez-López, M. 2021. Keyline in bean crop (*Phaseolus vulgaris L.*) for soil and water conservation. *Sustainability*, 13(17): 9982.

Diaz Grisales, V., Caicedo Vallejo, A.M. & Carabalí Muñoz, A. 2017. Ciclo de vida y descripción morfológica de Heilipus lauri Boheman (Coleoptera: *Curculionidae*) en Colombia. *Acta zoológica mexicana*, 33(2): 231–242. [Life cycle and morphological description of Heilipus lauri Boheman (Coleoptera: *Curculionidae*) in Colombia].

Dreistadt, S.H. 2007. *Integrated pest management for avocados*. Vol. 3503. UCANR Publications.

Dufour, R. 2015. *Tipsheet: Crop rotation in organic farming systems*. United States of America. National Center for Appropriate Technology (NCAT). In: ATTRA Sustainable Agriculture. https://attra.ncat.org/publication/tipsheet-crop-rotation-in-organic-farming-systems/

Dymond, K., Celis-Diez, J.L., Potts, S., Howlett, B., Willcox, B. & Garratt, M. 2021a. The role of insect pollinators in avocado production: A global review. *Journal of Applied Entomology*, 145(5). https://doi.org/10.1111/jen.12869.

Dymond, K., Celis-Diez, J.L., Potts, S.G., Howlett, B.G., Willcox, B.K. & Garratt, M.P. 2021b. The role of insect pollinators in avocado production: A global review. *Journal of Applied Entomology*, 145(5): 369–383.

Ehsan Ghane, Gary W. Feyereisen, Carl J. Rosen, Ulrike W. Tschirner. 2018. Agricultural drainage. Transactions of the ASABE. 61(3): 995-1000. https://doi.org/10.13031/trans.12642

El Khayat, M., Halwani, D.A., Hneiny, L., Alameddine, I., Haidar, M.A. & Habib, R.R. 2022. Impacts of climate change and heat stress on farmworkers' health: A scoping review. *Frontiers in public health*, 10: 71.

Erazo-Mesa, E., Ramírez-Gil, J.G. & Sánchez, A. 2021. Hass needs water irrigation in tropical precipitation regime: evidence from Colombia. *Water*.

Esteve-Llorens, X., Ita-Nagy, D., Parodi, E., González-García, S., Moreira, M.T., Feijoo, G. & Vázquez-Rowe, I. 2022. Environmental footprint of critical agro-export products in the Peruvian hyper-arid coast: A case study for green asparagus and avocado. *Science of the Total Environment*, 818. https://doi.org/10.1016/j.scitotenv.2021.151686

European Commission. 1998. Pan-European Criteria, indicators and operational level guidelines for sustainable forest management. Third Ministerial Conference on the protection of forests in Europe, Lisbon, Portugal.

Faber, B., Wilen, C., Eskalen, A., Morse, J., Hanson, B. & Hoddle, M. Updated regularly. *UC IPM Pest Management Guidelines: Avocado*. Davis.

FAO. 2011. FAO-ADAPT Framework program on climate change adaptation. Rome. www.fao.org/3/i2317e/i2317e.pdf

FAO. 2016. *Adapting agriculture to climate change*. Rome. www.fao.org/3/i6398e/i6398e.pdf

FAO. 2017a. *Addressing agriculture, forestry and fisheries in National Adaptation Plans*. Rome. www.fao.org/in-action/naps/resources/detail/en/c/1039752/

FAO. 2017b. *FAO Strategy on Climate Change*. Rome. www.fao.org/publications/card/en/c/I7175EN

FAO. 2017c. Technologies and Practices for Small Agricultural Producers (TECA). In: *Crop rotation in conservation agriculture*. Rome. [Cited 21 February 2023]. https://teca.apps.fao.org/teca/en/technologies/7415

FAO. 2018a. *Addressing sustainable crop production priorities in National Adaptation Plans*. Rome. www.fao.org/3/CA2930EN/ca2930en.pdf

FAO. 2018b. Promoting gender-responsive adaptation in the agriculture sectors: Entry points within National Adaptation Plans. Rome. www.fao.org/in-action/naps/resources/detail/ar/c/1114148/

FAO. 2019a. *Food Outlook - Biannual Report on Global Food Markets*. Rome. www.fao.org/3/ca4526en/ca4526en.pdf

FAO. 2019b. *Gender in adaptation planning for the agriculture sector – Guide for trainers*. Rome. www.fao.org/in-action/naps/resources/detail/en/c/1253017

FAO & UNDP (United Nations Development Programme). 2020a. *Toolkit for value chain analysis and market development integrating climate resilience and gender responsiveness*. Rome. www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1333257

FAO & UNDP. 2020b. *Using climate services in adaptation planning for the agriculture sectors*. Rome. www.fao.org/policy-support/tools-and-publications/resources-details/en/c/1371846/

FAO. 2020. *Major Tropical Fruits - Market Review 2019*. Rome. www.fao.org/3/cb0834en/CB0834EN.pdf

FAO. 2021a. Public expenditure analysis for climate change adaptation and mitigation in the agriculture sector – A case study of Uganda. Rome. [Cited 13 June 2023]

FAO. 2021b. Climate change, biodiversity and nutrition nexus – Evidence and emerging policy and programming opportunities. Rome. https://doi.org/10.4060/cb6701en

FAO. 2021c. Supporting developing countries to integrate their agriculture sectors into national adaptation plans. Rome. www.fao.org/3/cb5060en/cb5060en.pdf

FAO. 2021d. Climate smart agriculture case studies – projects from around the world. Rome. www.fao.org/3/cb5359en/cb5359en.pdf

FAO. 2021e. Tropical Fruit Market Reviews. Rome. www.fao.org/3/cc1900en/cc1900en.pdf

FAO. 2022a. Climate resilience and disaster risk analysis for gender-sensitive value chains – A guidance note. Rome. www.fao.org/3/cc0051en/cc0051en.pdf

FAO. 2022b. *Gender, agrifood value chains and climate resilient agriculture*. Rome. www.fao.org/3/cb9989en/cb9989en.pdf

FAO. 2022c. *Council Paper June 13-17th. FAO strategy on climate change 2022-2031*. Rome. www.fao.org/3/cc2274en/cc2274en.pdf

FAO. 2022d. *Major Tropical Fruits - Statistical Compendium 2021*. Rome. www.fao.org/3/cc2399en/cc2399en.pdf

FAO. 2022e. *Major Tropical Fruits - Market Review 2021*. Rome. www.fao.org/3/cc1900en/cc1900en.pdf

FAO. 2022f. *Greenhouse gas emissions from agrifood systems: Global, regional and country trends, 2000–2020*. FAOSTAT Analytical Brief Series No. 50. Rome, FAO. www.fao.org/3/cc2672en/cc2672en.pdf

FAO. 2023a. *Major Tropical Fruits Market Review – Preliminary results 2022*. Rome.

FAO. 2023b. FAOSTAT: Crops. In: *FAO*. Rome. [Cited 21 March 2023]. fao.org/faostat/en/#data/QC

FAO & UNDP. 2023. *Progress in developing a national monitoring and evaluation system for adaptation in the agriculture sector: multi-country case study - January 2023.* Rome, FAO. https://doi.org/10.4060/cc3916en

FAO & WUR (Wageningen University of Research). 2021. *Applying blockchain for climate action in agriculture: state of play and outlook*. The Hague and Rome. www.fao.org/3/cb3495en/cb3495en.pdf

Fan, J.,Lu, X.,Gu, S. & Xinyu, G. 2020a. Improving nutrient and water use efficiencies using water-drip irrigation and fertilization technology in Northeast China. *Agricultural Water Management*, 241: 106352. https://doi.org/10.1016/j.agwat.2020.106352.

Fausey, N.R. 2005b. Drainage, surface and subsurface. In: D. Hillel, ed. *Encyclopedia of Soils in the Environment*, pp. 409–413. Oxford, Elsevier.

Fischer, G., Alejandro Cleves-Leguizamo, J. & Enrique Balaguera-LÓPez, H. 2022. Impact of soil temperature on fruit species within climate change scenarios. *Impacto de la temperatura del suelo sobre los frutales en escenarios de cambio climático.*, 16(1): 1–13. https://doi.org/10.17584/rcch.2022v16i1.12769

Frankowska, A., Jeswani, H.K. & Azapagic, A. 2019. Life cycle environmental impacts of fruits consumption in the UK. *Journal of Environmental Management*, 248. https://doi.org/10.1016/j.jenvman.2019.06.012.

Garbanzo, M. 2015. *Curso producción de aguacate de bajura. Contenido Técnico: Establecimiento de plantaciones de aguacate*. Vol. 1. San José, Costa Rica.

García, J.A.O., González, Y.N., González, J.A.H., Maldonado, S.H.G. & Bravo, A.Á. 2017. Influence of climate and roughness on the tolerance to refrigeration of avocado 'Hass'. *Revista Mexicana de Ciencias Agrícolas*, 8 (19): 3911-3921. www.scielo.org.mx/scielo.php?script=sci_arttext&pid=S2007-09342017001103911&lng=es&nrm=iso&tlng=en.

García-Martínez, Y.G., Ballesteros, C., Bernal, H., Villarreal, O., Jiménez-García, L. & Jiménez-García, D. 2016. Traditional agroecosystems and global change implications in Mexico. *Bulgarian Journal of Agricultural Science*, 22(4): 548–565. https://www.agrojournal.org/.

George, O., Odhiambo, G.D., Wagai, S. & Kwach, J. 2019. An analysis of socioeconomic factors affecting avocado production in saline and flooded areas around Lake Victoria Basin of western Kenya. *African Journal of Agricultural Research*, 14(35): 2048–2061. https://academicjournals.org/journal/AJAR/article-abstract/4E2CDE762512.

Ghane, E. 2018. Agricultural Drainage. Michigan State University. www.egr.msu.edu/bae/water/drainage/sites/default/files/content/AgriculturalDrainage-2-2-18-WEB.PDF

Girkin, N.T., Dhandapani, S., Evers, S., Ostle, N., Turner, B.L. & Sjögersten, S. 2020. Interactions between labile carbon, temperature and land use regulate carbon dioxide and methane production in tropical peat. *Biogeochemistry*, 147(1): 87–97. https://doi.org/10.1007/s10533-019-00632-y.

Glenn, G.M., Orts, W., Imam, S., Chiou, B.-S. & Wood, D.F. 2014. Chapter 15 - Starch plastic packaging and agriculture applications. In: P.J. Halley & L. Avérous, eds. *Starch Polymers*, pp. 421-452. Amsterdam.

Goettsch, B., Urquiza-Haas, T., Koleff, P., Acevedo Gasman, F., Aguilar-Meléndez, A., Alavez, V., Alejandre-Iturbide, G. *et al*. 2021. Extinction risk of mesoamerican crop wild relatives. *Plants, People, Planet*, 3(6): 775–795. https://doi.org/10.1002/ppp3.10225.

González-Cortés, J.C., Vega-Fraga, M., Varela-Fregoso, L., Martínez-Trujillo, M., Carreón-Abud, Y. & Gavito, M.E. 2012. Arbuscular mycorrhizal fungal (AMF) communities and land use change: the conversion of temperate forests to avocado plantations and maize fields in central Mexico. *Fungal Ecology*, 5(1): 16–23. 10.1016/j.funeco.2011.09.002.

Government of Western Australia. 2017. *Growing avocados: Frost*, Department of Primary Industries and Regional Development. [Cited 09 February 2023]. www.agric.wa.gov.au/frost/growing-avocados-frost#:~:text=Irrigating%20the%20day%20prior%20to,by%20protecting%20the%20main%20trunk.

Graefe, S., Tapasco, J. & Gonzalez, A. 2013. Resource use and GHG emissions of eight tropical fruit species cultivated in Colombia. *Fruits (Paris)*, 68(4): 303–314. 10.1051/fruits/2013075

https://www.fruits-journal.org/action/displayAbstract?fromPage=online&aid=8953991&fulltextType=RA&fileId=S0248129413000753

Grüter, R., Trachsel, T., Laube, P. & Jaisli, I. 2022. Expected global suitability of coffee, cashew and avocado due to climate change. *PLoS ONE*, 17(1): 1–24. https://doi.org/10.1371/journal.pone.0261976

HAB (Hass Avocado Board) & CIRAD (Centre de Cooperation International en Recherche Agronomique pour le Développement). 2019a. Country profile: Mexico - Producer country profile produced by CIRAD, The Centre De Cooperation International En Recherche Agronomique Pour Le Développement, in collaboration with HAB, The Hass Avocado Board. California. https://hassavocadoboard.com/wp-content/uploads/2019/11/hab-marketers-country-profiles-2019-mexico.pdf

HAB & CIRAD. 2019b. *Country profile: Peru - Producer country profile produced by CIRAD, The Centre De Cooperation International En Recherche Agronomique Pour Le Développement, in collaboration with HAB, The Hass Avocado Board.* California. https://hassavocadoboard.com/wp-content/uploads/2019/11/hab-marketers-country-profiles-2019-peru.pdf

HAB & CIRAD. 2020. *Country profile: Chile - Producer country profile produced by CIRAD, The Centre De Cooperation International En Recherche Agronomique Pour Le Développement, in collaboration with HAB, The Hass Avocado Board.* California. https://hassavocadoboard.com/wp-content/uploads/hab-marketers-country-profiles-2020-chile.pdf

HAB & CIRAD. 2022. *Country profile: Colombia. Producer country profile produced by CIRAD, The Centre De Cooperation International En Recherche Agronomique Pour Le Développement, in collaboration with HAB, The Hass Avocado Board.* California. https://hassavocadoboard.com/wp-content/uploads/hab-marketers-country-profiles-2022-colombia.pdf

Haque, S., Akbar, D. & Kinnear, S. 2020. The variable impacts of extreme weather events on fruit production in subtropical Australia. *Scientia Horticulturae*, 262: 109050. https://doi.org/10.1016/j.scienta.2019.109050

He, D.A., He, M.H., Amalin, D.M., Liu, W., Alvindia, D.G. & Zhan, J.A. 2021. *Biological control of plant diseases: an evolutionary and eco-economic consideration*. https://doi.org/10.3390/pathogens10101311

Hernández-Valencia, A.S., Tapia-Vargas, L.M., Hernández-Pérez, A. & Larios-Guzmán, A. 2021.Evaluación de fertilizantes orgánicos y su efecto en la nutrición y desarrollo del aguacate. *Contribuciones tecnológicas para el futuro forestal y agropecuario Veracruzano*.

Herrera, T., Parejo, V. & González-Delgado, Á. 2022. Environmental analysis of avocado (*Laurus Persea L.*) oil production in north Colombia using the waste reduction algorithm. *CET Journal - Chemical Engineering Transactions*, 91: 235–240. https://doi.org/10.3303/CET2291040.

Holmes, M. & Farrell, D. 1993. Orchard microclimate as modified by windbreaks: a preliminary investigation. In: *South African Avocado Growers' Association Yearbook 1993*, pp. 59–64.

Hormaza, I. 2014. Factors influencing avocado fruit set and yield. From the Grove. *Verano*, 2014, 34–36.

Howden, M., Newett, S. & Deuter, P. 2005. Climate change-risks and opportunities for the avocado industry. Proceedings of the New Zealand and Australian Avocado Grower's Conference. Holland, P.(Eds.) Tauranga, New Zealand, pp. 1–28.

Hunter. 2023. *Drip irrigation design and installation guide*. Cited 18 February 2023. chwd.org/wp-content/uploads/Hunter-Drip-Irrigation-Design-Guide.pdf

InfoAgro. 2022. *Beneficios de la rotación de cultivos*. In: Infoagfro, Mexico. [Cited 3 March 2023]. https://mexico.infoagro.com/beneficios-de-la-rotacion-de-cultivos/ [Benefits from crop rotation].

IPCC (Intergovernmental Panel on Climate Change). 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, United States of America. https://doi.org/10.1017/9781009157896

IPCC. 2022. *Climate change 2022. Impacts, adaptation and vulnerability*. In: IPCC. www.ipcc.ch/report/ar6/wg2

IPCC. 2023. Summary for Policymakers. In: *Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, H. Lee and J. Romero (eds.)]. Geneva, Switzerland, 36 p.

International Model Forest Network. 2019. *Model Forest Toolkit - A how to manual*. Ottawa, Canada. https://imfn.net/wp-content/uploads/2019/03/Toolkit2019_Eng_All-in-One_FINAL.pdf

Irmer, S., Podzun, N., Langel, D., Heidemann, F., Kaltenegger, E., Schemmerling, B., Geilfus, C.-M., Zörb, C. & Ober, D. 2015. New aspect of plant–rhizobia interaction: alkaloid biosynthesis in Crotalaria depends on nodulation. *Proceedings of the National Academy of Sciences*, 112(13): 4164–4169.

Ish-Am, Gad. 2005. Avocado pollination - a review. New Zealand and Australia Avocado Growers' Conference, Tauranga New Zealand.

Johansson, E.L., Brogaard, S. & Brodin, L. 2022. Envisioning sustainable carbon sequestration in Swedish farmland. *Environmental Science & Policy*, 135: 16–25. https://doi.org/10.1016/j.envsci.2022.04.005.

Katzir, R. 2014. Advance farming in the desert - the Israeli experience. In A. El-Beltagy, W. Tao & M.C. Saxena, eds. pp. 535–541. Cairo, Egypt, International Dryland Development Commission (IDDC).

Kourgialasy, N.N. & Dokou, Z. 2021. Water management and salinity adaptation approaches of Avocado trees: A review for hot-summer Mediterranean climate. *Agricultural Water Management*, 252. https://doi.org/10.1016/j.agwat.2021.106923.

Lagumbay, V.F.K., Cabillar, D.M.A., Jumoc, R.M.A., Quiling, R.M.W. & Canencia, O.P. 2017. Food security and sustainability in the changing climate: the case of developing country. *International Journal for Research in Applied Science and Engineering Technology*, 5(11): 1577–1586. https://doi.org/10.22214/ijraset.2017.11227

Lahav, E., Whiley, W., Schaffer, B. & Wolstenholme, N. 2002. Irrigation and mineral nutrition. In: CABI, ed. *The avocado: botany, production and uses*, pp. 259–297.

Lahlali, R., Ezrari, S., Radouane, N., Kenfaoui, J., Esmaeel, Q., El Hamss, H., Belabess, Z. & Barka, E.A. 2022. Biological control of plant pathogens: A global perspective. *Microorganisms*, 10(3): 596.

Lal, N. & Sahu, N. 2017. Management strategies of sun burn in fruit crops-A Review. https://doi.org/10.20546/ijcmas.2017.606.131

Lang, T.D., S. & Lentini, R. 2023. *Water management for florida sugarcane Production 1*. University of Florida. IFAS Extension.

Liu, P. 2017. Socioeconomic impacts of climate change on the tropical fruit industry. How can the industry address them? Conference presentation at Symposium on Tropical Fruits, 23–25 October 2017. Fiji, International Tropical Fruit Network. http://itfnet.org/Download/ISTF2017/KEYNOTE.pdf

Livestock Engineering Unit & Environmental Practices Unit. 2005. Manure composting manual. Alberta – Agriculture, food and rural development. Canada. www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex8875/$file/400_27-1.pdf?OpenElement

Lobell, D.B., Field, C.B., Cahill, K.N. & Bonfils, C. 2006. Impacts of future climate change on California perennial crop yields: Model projections with climate and crop uncertainties. *Agricultural and Forest Meteorology*, 141(2): 208–218. https://doi.org/10.1016/j.agrformet.2006.10.006

López, R., González-Fernández, J., Galea, Z., Álvarez, J.M. & Iñaki, J.2015. Evaluation of composition and performance of composts derived from guacamole production residues. *Journal of Environmental Management*, 147: 132–139. https://doi.org/10.1016/j.jenvman.2014.09.016.

López Encina, C., Parisi, A., O'Brien, C. & Mitter, N. 2014. Enhancing somatic embryogenesis in avocado (*Persea americana Mill.*) using a two-step culture system and including glutamine in the culture medium. *Scientia Horticulturae*, 165: 44–50. https://doi.org/10.1016/j.scienta.2013.10.019

López Silva, A.A. & Vega Norori, I. 2004. *Cultivos de cobertura para sistemas de cultivos perennes. Guía Técnica*. Nicaragua, Universidad Nacional Agraria.

Lovatt, C. 2010. Alternate bearing of 'Hass' avocado: A summary of basic information to assist growers in managing their orchards California Avocado Soc. Yrbk. 125–140.

Lugo, A. 2018. Prácticas agroforestales en san Vicente del Caguán, una forma de conservar el medio ambiente. Universidad Nacional Abierta y a Distancia (UNAD).

Maes, M.J.A. 2022. *Monitoring exposure to climate-related hazards: Indicator methodology and key results*. OECD Environment Working Papers (OECD): no. 201. OECD. Paris.

Martín Gil, A. & Aranda Aranda, G. 2021. *Guía de gestión integrada de plagas para el cultivo de aguacate*. Madrid. Ministerio de Agricultura, Pesca y Alimentación. [*Integrated Pest Management Guide for avocado cultivation*. Madrid, Ministry of Agriculture, Fisheries and Food.].

Marulanda, A., Ruiz-Ruiz, M. & Cortes-Rodríguez, M. 2018. Influence of spray drying process on the quality of avocado powder: a functional food with great industrial potential. *Vitae*, 25(1): 37-48.

Mary, N. 2020. The use of cover crops to increase yield and reduce pest pressure in a commercial avocado orchard at Levubu, Limpopo province.

Mendes, L.R.D. 2021. Nitrogen removal from agricultural subsurface drainage by surface-flow wetlands: variability. *Processes*, 9(1): 156.

Mesa E., Guillermo Ramírez-Gil, J. & Echeverri Sánchez, A. 2021. Avocado cv. Hass needs water irrigation in tropical precipitation regime: Evidence from Colombia. *Water* 2021, 13(14). https://doi.org/10.3390/w13141942

Michel, K., Weninger, T., Scheper, S., Lackóová, L., Kitzler, K., Gartner, K., King, N.W., Cornelis, W. & Strauss, P. 2021. Ecosystem services of tree windbreaks in rural landscapes - a systematic review. *Environmental Research Letters*, 16(10). https://103002. https://doi.org/10.1088/1748-9326/ac1d0d.

Mitra, S.K. 2016. Climate change: impact, and mitigation strategies for tropical and subtropical fruits. *VI International Symposium on Tropical and Subtropical Fruits 1216*. p. 1–12. https://doi.org/10.17660/ActaHortic.2018.1216.1

Mohale, M.P., Manyevere, A., Parwada, C. & Zerizghy, M. 2022. Effect of eucalyptus-wood-based compost application rates on avocado (*Persea americana Mill.*) foliar nutrient content and fruit yield. *Agronomy*, 12(2): 477.

Montiel-Aguirre, G., Krishnamurthy, L., Vázquez-Alarcón, A. & Uribe-Gómez, M. 2008. Opciones agroforestales para productores de aguacate. *Terra Latinoamericana*, 26(1): 85–90. [Agroforestry options for avocado producers. *Terra Latinoamericana*, 26(1): 85–90.].

Nataren Velazquez, J., del Ángel Pérez, A. L., Megchún-García, J. V., Ramírez Herrera, E., & Meneses Márquez, I. 2020. Productive characterization of avocado (*Persea americana Mill*.) in the high mountain area Veracruz, Mexico.

Nath, V., Kumar, G., Pandey, S.D. & Pandey, S. 2019. *Impact of Climate Change on Tropical Fruit Production Systems and its Mitigation Strategies*. Climate Change and Agriculture in India: Impact and Adaptation pp 129–146. Springer, Cham. https://www.researchgate.net/publication/327632231_Impact_of_Climate_Change_on_Tropical_Fruit_Production_Systems_and_its_Mitigation_Strategies

Nieto Flores, D. 2017. *Inducción de variabilidad en aguacate cv. Hass mediante mutagénesis radioinducida*. Universidad Autónoma del Estado de México. Mexico.

Oberschelp, J., Harrand, L., Mastrandrea, C., Salto, C., & Florez, M. 2020. *Cortinas forestales: rompevientos y amortiguadoras de deriva de agroquímicos*. EEA Concordia. Instituto Nacional de Tecnología Agropecuaria. Ediciones INTA. Buenos Aires.

Oloo, J., Makenzi, P., Mwangi, J. & Abdulrazack, A. 2013. Dominant tree species for increasing ground cover and their distribution in Siaya County, Kenya. *IJAIR*, 2(3): 373–377.

Omar, A.E.-D. 2014. Bagging of bunches with different materials influences yield and quality of Rothana date palm fruit. *Journal of Food Agriculture and Environment*, Volume 2: 520–522.

Ortega, G.M. 2022. *Manejo del estrés hídrico en aguacate: efectos en la productividad y en el control de la podredumbre blanca radicular*. España. UMA Editorial.

Osorio-Almanza, L., Burbano-Figueroa, Ó., Arcila, C.A., Vásquez, B.A., Carrascal-Pérez, F., & Romero, F.J. 2017. *Distribución espacial del riesgo potencial de marchitamiento del aguacate causado por Phytophthora cinnamomi en la subregión de Montes de María, Colombia*. Colombia.

Parker, L., Pathak, T. & Ostoja, S. 2021. Climate change reduces frost exposure for high-value California orchard crops. *Science of the Total Environment*, 762. https://doi.org/10.1016/j.scitotenv.2020.143971

Pattemore, D., Buxton, M., Cutton, B., McBrydie, H., Goodwin, R.M., & Dag, A. 2018. Low overnight temperatures associated with a delay in 'Hass' avocado (*Persea americana*) female flower opening, leading to nocturnal flowering. https://doi.org/10.26786/1920-7603(2018)12

Peña Mojica, J. & Carabalí, A. 2018. Effect of honeybee (*Apis mellifera L.*) density on pollination and fruit set of avocado (*Persea americana Mill.*) Cv. Hass. *Journal of Apicultural Science*, 62. https://doi.org/10.2478/jas-2018-0001

Pérez Galarce, F. 2016. Sistemas de alerta temprana para el control de alternaria en tomate. *Villa Alegre*, 338.

Polón, R., Ruiz, M., Dell'Amico, J., Morales, D., Jerez, E., Ramírez, M. & Maqueira, L. 2011. *Principales beneficios que se alcanzan con la práctica adecuada del drenaje agrícola*. Instituto Nacional de Ciencias Agrícolas.

Puno, G.R., Puno, R.C. & Maghuyop, I.V. 2021. Two-dimensional flood model for risk exposure analysis of land use/land cover in a watershed. *Global Journal of Environmental Science and Management*, 7(2): 225–238. https://doi.org/10.22034/gjesm.2021.02.06

Ramírez-Gil, J.G., Martínez, G.O.G. & Morales Osorio, J.G. 2018. Design of electronic devices for monitoring climatic variables and development of an early warning system for the avocado wilt complex disease. *Computers and Electronics in Agriculture*, 153: 134–143. https://doi.org/10.1016/j.compag.2018.08.002.

Ramirez-Gil, J.G., Henao-Rojas, J.C. & Morales-Osorio, J.G. 2020. Mitigation of the Adverse Effects of the El Niño (El Niño, La Niña) Southern Oscillation (ENSO) Phenomenon and the Most Important Diseases in Avocado cv. Hass Crops. *PLANTS-BASEL*, 9(6): 790. https://doi.org/10.3390/plants9060790.

Ranjan, P., Patle, G.T., Prem, M. & Solanke, K.R. 2017b. Organic Mulching- A Water Saving Technique to Increase the Production of Fruits and Vegetables. *Current Agriculture Research Journal*, 5(3). https://doi.org/10.12944/CARJ.5.3.17.

Reeksting, B.J., Olivier, N.A. & van den Berg, N. 2016. Transcriptome responses of an ungrafted Phytophthora root rot tolerant avocado (*Persea americana*) rootstock to flooding and *Phytophthora cinnamomic. BMC Plant Biol*.

Remy, S., Carvalho, L.J., Jakopic, J., *et al.* 2019. *Protecting fruit production from frost damage minipaper 01: Frost protection by above crown sprinkling*. EIP-AGRI Focus Group. https://eu-cap-network.ec.europa.eu/sites/default/files/publication/2023-05/eip-agri _fg_renewable_energy_on_the_farm_final_report_2019_en.pdf

Rocha-Arroyo, J.L., Salazar-García, S., Bárcenas-Ortega, A., González-Durán, I. & Cossio-Vargas, L. 2011. Fenología del aguacate ´Hass´en Michoacán. *Revista Mexicana de Ciencias Agrícolas*, 2(3): 303–316.

Rodríguez Pleguezuelo, C.R., Francia Martínez, J.R., García Tejero, I.F., Gálvez Ruíz, B., Franco Tarifa, D. & Durán Zuazo, V.H. 2018. Chapter 14 - Avocado (*Persea americana Mill*.) trends in water-saving strategies and production potential in a Mediterranean climate, the study case of Spain: A Review. In: I.F. García Tejero & V.H. Durán Zuazo, eds. *Water Scarcity and Sustainable Agriculture in Semiarid Environment*, pp. 317–346. Academic Press.

Rodríguez Y., G., Palacios, S., Benavides, D., Vallejo, B., López, J., Betancourt Vásquez, M. & Patiño, A. 2017. *Cultivo de Aguacate: Prácticas y recomendaciones de manejo integrado*. Corporación Universitaria Santa Rosa de Cabal (UNISARC).

Rubina Sherpa, R.D., Sadashiv Narayan Bolbhat, Tukaram Dayaram Nikam and Suprasanna Penna 2022. Gamma radiation induced in-vitro mutagenesis and isolation of mutants for early flowering and phytomorphological variations in dendrobium ‘Emma White’. https://doi.org/10.3390/plants11223168

SAAGA (South African Grower Association). 2023. SAGA. South Africa. [Cited 20 April 2023]

Saavedra, J., Córdova, A., Navarro, R., Díaz-Calderón, P., Fuentealba, C., Astudillo-Castro, C., Toledo, L., Enrione, J. & Galvez, L. 2017. Industrial avocado waste: Functional compounds preservation by convective drying process. *Journal of Food Engineering*, 198: 81–90.

SAGARPA (Secretaría de Agricultura, Desarrollo Rural, Pesca y Alimentación) n.d. Manual básico de apícola. Programa Nacional para el control de la abeja africana. In: Coordinación General de Ganadería. SAGARPA. Mexico. https://osiap.org.mx/senasica/sites/default/files/manual%20basico%20apicultura%20sagarpa.pdf

Sagwe, R.N., Peters, M.K., Dubois, T., Steffan-Dewenter, I. & Lattorff, H.M.G. 2021. Pollinator supplementation mitigates pollination deficits in smallholder avocado (Persea americana Mill.) production systems in Kenya. *Basic and Applied Ecology*, 56: 392–400. https://doi.org/10.1016/j.baae.2021.08.013.

Sagwe, R.N., Peters, M.K., Dubois, T., Steffan-Dewenter, I. & Lattorff, H.M.G. 2022. Pollinator efficiency of avocado (Persea americana) flower insect visitors. *Ecological Solutions and Evidence*, 3(4). https://doi.org/10.1002/2688-8319.12178.

Salazar-López, N.J., Domínguez-Avila, J.A., Yahia, E.M., Belmonte-Herrera, B.H., Wall-Medrano, A., Montalvo-González, E. & González-Aguilar, G.A. 2020. Avocado fruit and by-products as potential sources of bioactive compounds. *Food Research International*, 138: 109774. https://doi.org/10.1016/j.foodres.2020.109774.

Sarminah, S., Karyati, Hartono T. & Afandi, F. 2021. Implementation of land rehabilitation to reduce soil erosion and surface runoff by sengon (*Falcataria moluccana*) and jabon (*Antocephalus cadamba*) plantation. https://doi.org/10.2991/absr.k.220102.037

Sarminah, S., Sinaga, D.S.P., Crisdayanti, R. & Syafrudin, M. 2021. Effect of organic mulch on runoff and erosion rates in abandoned land. proceedings of the joint symposium on tropical studies (JSTS-19), pp. 308–314. Atlantis Press.

Sauca, E. & Urabayen, D. 2005. Rotaciones y asociaciones de cultivos. *Monográficos Ekonekazaritza*, (7).

Saucedo & Martínez, N., & Chávez Larios, J. A. 2020. Sistema contra heladas, un recurso para aumentar la productividad en cultivos con entornos cerrados en el Occidente de México. [Frost protection system, a resource to increase productivity in crops with closed environments in Western Mexico].

Schaffer, B., Wolstenholme, B.N., Whiley, A.W 2013. The Avocado Botany, production and uses 2nd edition. https://doi.org/10.1079/9781845937010.0000

Scheelbeek, P.F.D., Moss, C., Kastner, T. *et al.* 2020. United Kingdom's fruit and vegetable supply is increasingly dependent on imports from climate-vulnerable producing countries. Nat Food 1, 705–712 p. https://doi.org/10.1038/s43016-020-00179-4

Schick, A., Wieners, E., Schwab, N. & Schickhoff, U. 2018. Sustainable disaster risk reduction in mountain agriculture: Agroforestry experiences in Kaule, mid-hills of Nepal. *Climate Change, Extreme Events and Disaster Risk Reduction: Towards Sustainable Development Goals:* 249–264.

Seed Change. 2018. *Agroforestry: diversifying farms for increased resilience in Central America*. Seed Change, Canada. https://weseedchange.org/wp-content/uploads/2019/09/SeedChange_program-highlight_ agroforestry-Central-America.pdf

Seydou, T.H., Agali, A., Aissatou, S., Seydou, T.B., Issaka, L. & Ibrahim, B.M. 2023. Evaluation of the impact of seasonal agroclimatic information used for early warning and farmer communities' vulnerability reduction in Southwestern Niger. *Climate*, 11(31). https://doi.org/10.3390/cli11020031.

Silva, I.R.A., Magnani, M., de Albuquerque, F.S.M., Batista, K.S., Aquino, J.d.S. & Queiroga-Neto, V. 2017. Characterization of the chemical and structural properties of native and acetylated starches from avocado (*Persea americana Mill*.) seeds. *International Journal of Food Properties*, 20(sup1): S279–S289. https://doi.org/10.1080/10942912.2017.1295259

Singh, R. 2023. Wind Erosion. In: R. Singh, ed. *Soil and Water Conservation Structures Design*, pp. 297–322. Singapore, Springer Nature Singapore.

Sloand, E., Killion, C., Gary, F., Dennis, B., Glass, N., Hassan, M., Campbell, D. & Callwood, G. 2015. Barriers and facilitators to engaging communities in gender-based violence prevention following a natural disaster. *J Health Care Poor Underserved*, 26(4). https://doi.org/10.1353/hpu.2015.0133

Soler A., N.T., Masson J., Hoarau I., Tisserand G., Thuriès L., Rostislavleva, K., Zhang, L. *et al.*, 2020. Livret technique ANANABIO: Innovations techniques pour la culture de l'ananas en agriculture biologique à la Réunion. [Cited 15 June 2023]. https://www.researchgate.net/publication/349502240_Livret_technique_ANANABIO_Innovations_techniques_pour_la_culture_de_l'ananas_en_agriculture_biologique_a_la_Reunion

Scherr, S.J. & Sthapit S. 2009. *Mitigating climate change through food and land use*. Worldwatch Report No. 179. Worldwatch Institute and EcoAgriculture Partners, Washington DC, United States of America.

Sthapit, B.R., Ramanatha Rao, V. & Sthapit, S.R. 2012. *Tropical fruit tree species and climate change*. Bioversity International, New Delhi, India. 142 p. ISBN: 978-92-9043909-7 https://cgspace.cgiar.org/items/d7230c3b-5777-4734-a4f3-d35f2a37a7b7

Steyn, T.C. 2020. Comparing hail risk management strategies through whole-farm multi-period stochastic budgeting for avocado production in South Africa. PhD Thesis. Stellenbosch: Stellenbosch University.

Tamayo-Ramos, D.I., Salazar-González, J.A., Casson, S.A. & Urrea-López, R. 2022. Old and new horizons on Persea americana transformation techniques and applications. *Plant Cell, Tissue & Organ Culture*, 150(2): 253–266. https://doi.org/10.1007/s11240-022-02268-7

Tapia-Vargas, M., Pedraza Santos, M.E., Larios-Guzmán, A., Vidales-Fernández, I., Guillén-Andrade, H. & Barradas-Vázquez, V.L. 2012. Variabilidad espacial de la lluvia por efecto de un sistema antigranizo en la franja aguacatera de Michoacán. *Revista Fitotecnia Mexicana*, 35(5): 91–96.

Teem, J.L., Alphey, L., Descamps, S., Edgington, M.P., Edwards, O., Gemmell, N., Harvey-Samuel, T. *et al.* 2020. Genetic biocontrol for invasive species. *Frontiers in Bioengineering and Biotechnology*, 8. https://doi.org/10.3389/fbioe.2020.00452

Thorp, G. 2011. *Avocado alternate bearing research*. Horticulture Australia. https://www.horticulture.com.au/globalassets/hort-innovation/historic-reports/avocado-alternate-bearing-research-av10010.pdf

Tinyane, P., Soundy, P. & Sivakumar, D. 2018. Growing 'Hass' avocado fruit under different coloured shade netting improves the marketable yield and affects fruit ripening. *Scientia Horticulturae*, 230: 43–49. https://doi.org/10.1016/j.scienta.2017.11.020

United Nations. 2023. UN Comtrade Database. Department of Economic and Social Affairs. [Cited 6 March 2023]. https://comtradeplus.un.org

United Nations Environment Programme. 2015. Microfinance for ecosystem-based adaptation measures – Options, costs and benefits. Panama.

UNFCCC (United Nations Framework Convention on Climate Change). 2023. The Paris Agreement – What is the Paris Agreement? [Cited 2 May 2023] https://unfccc.int/process-and-meetings/the-paris-agreement#:~:text=It%20entered%20into%20force%20on,above%20pre%2Dindustrial%20levels.%E2%80%9D

UNFCCC. 2024. Global goal on adaptation. Untied Nations Convention on Climate Change. [Cited 23 January 2024]. https://unfccc.int/topics/adaptation-and-resilience/workstreams/glasgow-sharm-el-sheikh-WP-GGGA#:~:text=The%20Paris%20Agreement%20of%202015,the%20goal%20of%20holding%20global

Uno, Y., Okubo, H., Itoh, H. & Koyama, R. 2016. Reduction of leaf lettuce tip burn using an indicator cultivar. *Scientia Horticulturae*, 210: 14–18. https://doi.org/10.1016/j.scienta.2016.07.001

Vásquez, R., Ballesteros, H., Castañeda, S., Riveros, L., Ortega, C. & Calvo, N. 2011. Polinización dirigida con abejas *Apis mellifera*: Tecnología para el mejoramiento de la producción de cultivos con potencial exportador. Bogotá: *Corpoica*.

Wangithi, C., Muriithi, B.W., Diiro, G., Dubois, T., Mohamed, S., Lattorff, M., Ngowi, B.V., Abdel-Rahman, E., Adan, M. & Kassie, M. 2022. Synergies of integrated pest and pollinator management in avocado farming in East Africa: An ex-ante economic analysis. *PLoS ONE*, 17(7). https://doi.org/10.1371/journal.pone.0271241

World Bank. 2022. Country risk profile reports. Rome. [Cited 3 February 2023]. https://datacatalog.worldbank.org/search/dataset/0041074

World Bank. 2022. Climate Change Knowledge Portal for development practitioners and policymakers. In: World Bank Group [online]. Washington. [Cited 7 October 2022]. https://climateknowledgeportal.worldbank.org

WMO (World Meteorological Organization). 2022. *Global status of multi-hazard early warning systems: Target G*. Geneva, Switzerland, United Nations Office for Disaster Risk Reduction. https://library.wmo.int/doc_num.php?explnum_id=11333

Zhang, D. & Guo, P. 2016. Integrated agriculture water management optimization model for water saving potential analysis. *Agricultural Water Management*, 170: 5–19. https://doi.org/10.1016/j.agwat.2015.11.004

Table 6.

Caldana, N.F.d.S., Nitsche, P., Martelócio, A., Rudke, A., Zaro, G., Batista Ferreira, L., Contador Zaccheo, P., Colucci de Carvalho, S. & Martins, J. 2019. Agroclimatic risk zoning of avocado (*Persea americana*) in the hydrographic basin of Paraná River III, Brazil. *Agriculture*, 9(12). https://doi.org/10.3390/agriculture9120263.

Howden, M., Newett, S. & Deuter, P. 2005. Climate change-risks and opportunities for the avocado industry. *Proceedings of the New Zealand and Australian Avocado Grower's Conference*. Holland, P.(Eds.) Tauranga, New Zealand, pp. 1–28. www.avocadosource.com/Journals/AUSNZ/AUSNZ_2005/HowdenMark2005.pdf

Rocha-Arroyo, J.L., Salazar-García, S., Bárcenas-Ortega, A., González-Durán, I. & Cossio-Vargas, L. 2011. Fenología del aguacate ´Hass´en Michoacán. *Revista Mexicana de Ciencias Agrícolas*, 2(3): 303–316.

Table 10.

Alves Silva, I., Magnani, M., Medeiros de Albuquerque, F., Sabino Batista, K, Souza Aquino, J. & Queiroga-Neto, V. 2017. Characterization of the chemical and structural properties of native and acetylated starches from avocado (*Persea americana Mill.*) seeds, *International Journal of Food Properties*. 20. https://doi.org /10.1080/10942912.2017.1295259

Saavedra, J., Córdova, A., Navarro, R., Díaz-Calderón, P., Fuentealba, C., Astudillo-Castro, C., Toledo, L., Enrione, J. & Galvez, L. 2017. Industrial avocado waste: Functional compounds preservation by convective drying process. *Journal of Food Engineering*, 198: 81–90.

Tesfaye, T., Ayele, M., Gibril, M., Ferede, E., Limeneh, D. Y. & Kong, F. 2022. Beneficiation of avocado processing industry by-product: A review on future prospect. *Current Research in Green and Sustainable Chemistry*, 5, 100253.

Glenn, G. M., Orts, W., Imam, S., Chiou, B. S. & Wood, D. F. 2014. Starch plastic packaging and agriculture applications. In *Starch Polymers*. 421–452.

Marulanda, A., Ruiz-Ruiz, M. & Cortes-Rodríguez, M. 2018. Influence of spray drying process on the quality of avocado powder: a functional food with great industrial potential. *Vitae*, 25(1): 37–48.

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