5SM

Food, Fibre and Other Ecosystem Products
Supplementary Material

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Table of Contents

5SM

SM5.1 Observed Impacts on Major Crops

SM5.1.1 Methodology

To review progress in the detection and attribution studies in the crop-based system since AR5, we collected literature mainly from SCOPUS using the following search terms.

PUBYEAR > 2013 AND PUBYEAR < 2021 AND (TITLE-ABS((flood OR "sea level rise" OR "extreme event" OR yield OR drought OR *stability) AND crop* AND impact*) OR AUTHKEY((flood OR "sea level rise" OR "extreme event" OR yield OR drought OR *stability) AND crop* AND impact*)) AND (TITLE-ABS({greenhouse gas} OR {global warming} OR {climate change} OR {climatic change} OR {climate variability} OR {climate warming}) OR AUTHKEY({greenhouse gas} OR {global warming} OR {climate change} OR {climatic change} OR {climate variability} OR {climate warming})) AND NOT ((TITLE-ABS(emissions OR mitigation OR REDD OR MRV) OR AUTHKEY(emissions OR mitigation OR REDD OR MRV)))

From the search results, we selected studies that include search strings related to detection and attribution of the observed impacts in titles, abstracts, or authors' keywords. They include 'historical', 'yield record', 'attribution' and 'detection'. Selected studies were manually checked for eligibility using the following criteria: The effects of climatic factors on variables related to crop production are tested statistically or with mechanistic crop models based on long-term records. Another focused search was conducted through Google Scholar to obtain studies using counterfactual climate data to determine the effects of human-induced climate change on agricultural productitivity, which resulted in additional two studies (Moore and Lobell, 2015; Ortiz-Bobea et al., 2021). These studies were broadly grouped into long-term effects and short-term weather sensitivity, which are summarised in Table SM5.1.

Further assessment was made on the long-term effect of climate change. Periods of the studies differed among studies, ranging from 20 to 50 years. Global-scale studies were included, but their regional breakdowns were used for the assessment by sub-regions. The effects of climate change were classified into 'positive', 'negative', 'mixed' or 'neutral'. Robustness in the attribution of the climate change impacts is based on the statistical significance.

Individual observations were summarised using the weighted score of the effects: effect score = 1 for positive, –1 for negative, 0 for mixed or neutral. The effect scores were then averaged for each crop and sub-region to represent the climate change impact, which is shown in Figure 5.3. The overall assessment is positive when the averaged score is greater than 0.3, negative when smaller than –0.3, and mixed when between –0.3 and 0.3. Confidence of the assessment is based on the robustness of the attribution and the number of references available. Robustness score is 2 for 'high', 1 for 'medium' and 0 for 'low'. These were multiplied by the number of studies to estimate overall confidence scores in each region and crop. We rated 'high' when the robustness score is greater than 4, 'low' when it is less than 3, and 'medium' when it is in between, which is also indicated in Figure 5.3.

Table SM5.1 | Observed impacts on major crops by crops and IPCC sub-region

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Long-term effect of climate change						
Maize						
Global	1981–2010	Negative	Crop production loss attributable to anthropogenic climate change amounts to 22.3 B$ yr^{-1} or 4.1% (–0.5% to 8.5%), globally.	CO_2/temperature/ precipitation	High but regionally dependent	Iizumi et al. (2018)
Global	1974–2008	Mixed	Yield change due to climate change was +0.0% globally, but mixed effects depending on regions.	Temperature/ precipitation	High but regionally dependent	Ray et al. (2019a)
Northern Africa	1981–2010	Negative	Significantly negative impacts on yield.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Northern Africa	1974–2008	Negative	Maize yield reduced by 4.3% during the period.	Temperature/ precipitation	High	Ray et al. (2019a)
Sub-Saharan Africa	1962–2014	Negative	Increasing temperature partially offset the increase in maize yield (1% yr^{-1}) due to technological improvement. A degree warming reduced maize yield by 0.8% (10 kg/ha).	Temperature/ precipitation	Medium	Hoffman et al. (2018a)
Sub-Saharan Africa	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Sub-Saharan Africa	1974–2008	Negative	Maize yield reduced by 5.8% during the period.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Positive	Maize yield reduced by 5.1% during the period.	Temperature/ precipitation	High	Ray et al. (2019a)
Eastern Asia	1980–2010	Negative	Maize growth duration decreased by 9–19 d. Yield potential of historical varieties decreased by 0.043 t ha^{-1} yr^{-1}. Later-maturing cultivars alleviated the decline.	Temperature/ precipitation	High	Bu et al. (2015)

5SM

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Eastern Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Eastern Asia	1980–2009	Positive	7–17% yield increase per decade. The northward limit shifted by more than 290 km. The overall yield gain 35%. Warming has benefited maize production with adaptation technology.	Temperature	High	Meng et al. (2014)
Eastern Asia	1981–2009	Negative	Decreases in mean temperature, precipitation and solar radiation over maize growth period jointly reduced yield most by 13.2–17.3% in southwestern China.	Temperature, precipitation, solar radiation	High	Tao et al. (2016a)
Eastern Asia	1981–2009	Positive	Increases in mean temperature, precipitation and solar radiation jointly increased yield most by 12.9–14.4%.	Temperature, precipitation, solar radiation	High	Tao et al. (2016a)
Eastern Asia	1981–2009	Neutral	No detectable changes in Zone I.	Temperature, precipitation, solar radiation	Low	Tao et al. (2016a)
Eastern Asia	1981–2009	Neutral	No detectable changes in Zone I.	Temperature, precipitation, solar radiation	Low	Tao et al. (2016a)
Eastern Asia	1981–2009	Neutral	No detectable changes in Zone I.	Temperature, precipitation, solar radiation	Low	Tao et al. (2016a)
Eastern Asia	1981–2009	Negative	Positive yield trend (1.5% yr^{-1}).	Solar radiation, temperature, rainfall	High	Xiao and Tao (2014)
Eastern Asia	1981–2009	Negative	Positive yield trend (1.3% yr^{-1}).	Solar radiation, temperature, rainfall	High	Xiao and Tao (2014)
Eastern Asia	1981–2009	Negative	Positive yield trend (1.4% yr^{-1}).	Solar radiation, temperature, rainfall	High	Xiao and Tao (2014)
Eastern Asia	1981–2009	Negative	Positive yield trend (1.1% yr^{-1}).	Solar radiation, temperature, rainfall	High	Xiao and Tao (2014)
Eastern Asia	1980–2009	Mixed	For the whole country, planting-area-weighted average of yield change due to trends in mean temperature and precipitation together was about 1.16%, −0.31%, −0.40% and 0.11% over the whole period for rice, wheat, maize and soybean, respectively.	Solar radiation, temperature, rainfall	Medium	Zhang et al. (2016c)
Southern Asia	1981–2010	Negative	Significantly negative impacts	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Positive	Maize yield reduced by 1.0% during the period.	Temperature/ precipitation	High	Ray et al. (2019a)
Southeastern Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Western Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1981–2010	Mixed	Both positive and negative effects were observed in the region.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1974–2008	Negative	Maize yield decreased by 1.2%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central and South America	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Central and South America	1974–2008	Positive	Maize yield increased by 2.7% during the period.	Temperature/ precipitation	High	Ray et al. (2019a)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Central and South America	1971–2012	Negative	The effect of climate trends for the whole period was –5.4% for maize. Crop yield gains for this period could have been 15–20% higher if climate trend was not significant.	Precipitation/air temperature	High	Verón et al. (2015)
Eastern Europe	1981–2010	Neutral	Almost non-significant changes.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Eastern Europe, Northern Europe	1974–2008	Negative	Maize yield decreased by 24.5%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Southern Europe	1961–2014	Negative	Adverse climatic condition had a negative impact on maize yield increase over time by 19% in Italy and 6% in Spain. Temperature trend is responsible for a reduction in the long-run growth rate of yield in wheat.	Air temperature	High	Agnolucci and De Lipsis (2020)
Southern Europe	1981–2010	Negative	Mostly significantly negative effects.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Southern Europe	1989–2009	Negative	Impacts on maize during the period. Greece, 9.8% Spain, –2.4% Italy, –7.9% Portugal, –6.0%	Temperature/ precipitation	High	Moore and Lobell (2015)
Southern Europe, Western Europe	1974–2008	Negative	Maize yield decreased by 6.3%.	Temperature/ precipitation	High	Ray et al. (2019a)
Western Europe	1961–2014	Neutral	A small positive impact of weather on the size of the yield trend in Belgium (1.6%), France (5.02%) and Germany (3.18%). Temperature trend is responsible for a reduction in the long-run growth rate of yield in wheat.	Air temperature	High	Agnolucci and De Lipsis (2020)
Western Europe	1981–2010	Mixed	At the northern border, some positive effects, but negative effects in southern stages.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Western Europe	1989–2009	Positive	Impacts on maize during the period. Belgium, 12.0% Germany, 6.2% France, 0.9% the Netherlands, 4.5%	Temperature/ precipitation	Medium	Moore and Lobell (2015)
Northern America	1981–2010	Mixed	At the northern border, some positive effects, but negative effects in southern stages.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Northern America	1974–2008	Neutral	Maize yield decreased by 0.5%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Rice						
Global	1981–2010	Neutral	Crop production loss attributable to anthropogenic climate change: 0.8 B$, or 1.8% (–12.4% to 9.6%) for rice. Rising CO_2, increasing temperatures, changes in precipitation (not shown individually).	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Global	1974–2008	Mixed	Yield change due to climate change. –0.3%, rice (% relative to the average between 1974 and 2008) Rising temperature, variable precipitation.	Temperature/ precipitation	High	Ray et al. (2019a)
Northern Africa	1981–2010	Mixed	Mixed effects depending on regions.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Northern Africa	1974–2008	Negative	Rice yield was decreased by 1.3%.	Temperature/ precipitation	High	Ray et al. (2019a)

5SM

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Sub-Saharan Africa	1981–2010	Mixed	Both negative and positive effects in the regions.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Sub-Saharan Africa	1974–2008	Negative	Rice yield was decreased by 3.1% during the period.	Temperature/ precipitation	High	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Positive	Rice yield was increased by 0.9% during the period. Impacts were significant in 89% of the harvested areas.	Temperature/ precipitation	High	Ray et al. (2019a)
Eastern Asia	1981–2010	Positive	Significantly positive impacts	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Eastern Asia	1980–2012	Mixed	Average change in rice yield was +0.52% for early rice and 2.83% for late rice during the 1980–2012 period, if averaged over eight provinces. However, the effects were mixed depending on the provinces.	Temperature/ precipitation/solar radiation	Low	Liu et al. (2016)
Eastern Asia	1961–2003	Positive	Rising CO_2 accounts for 1–7% in the increase in rice yield. Six of nine provinces showed negative effects of rising temperature, but the positive effects of CO_2 were greater than the negative effects of rising temperature.	CO_2/temperature	Medium	Sawano et al. (2015)
Eastern Asia	1949–2015	Mixed	Increase in rice yield (0–1.0 t ha^{-1}°C^{-1}) in northern provinces, but decrease (–0.6 to 0 t ha^{-1}°C^{-1}) in southern provinces of China. Rice yield at the country level decreased by 0.05 t ha^{-1}°C^{-1}.	Temperature	High	Wang and Hijmans (2019)
Eastern Asia	1981–2012	Positive	Climate trend had a positive effect (4.91–2.12%), but extreme events had negative effects on rice yield (–2.6% to –15.9%) followed by climate fluctuation (–2.6% to –4.4%) in the period studied.	Temperature	High	Wang et al. (2018)
Eastern Asia	1981–2009	Positive	Yield increased by 5.83%, 1.71%, 8.73% and 3.49% in early, late and single rice, as a result of greater growing degree days. Heat stress increased slightly (0.14–1.34%), but chilling injury decreased. Reducing solar radiation had a negative impact on yield.	Temperature/solar radiation	High	Zhang et al. (2016b)
Eastern Asia	1980–2009	Mixed	For the whole country, planting-area-weighted average of yield change due to trends in mean temperature and precipitation together was about 1.16%, –0.31%, –0.40% and 0.11% over the whole period for rice, wheat, maize and soybean, respectively.	Solar radiation/ temperature/ rainfall	Medium	Zhang et al. (2016c)
Eastern Asia	1981–2009	Positive	Yield trend at Xinbin: 175 kg ha^{-1} yr^{-1} or 4.5% yr^{-1} (significant).	Temperature/ solar radiation/ precipitation	High	Zhang et al. (2016a)
Eastern Asia	1981–2009	Negative	Yield trend at Ganyou: 88 kg ha^{-1} yr^{-1} or 1.4% yr^{-1}.	Temperature/ solar radiation/ precipitation	High	Zhang et al. (2016a)
Eastern Asia	1981–2009	Negative	Yield trend at Minyang: 41 kg ha^{-1} yr^{-1} or 0.54% yr^{-1}.	Temperature/ solar radiation/ precipitation	High	Zhang et al. (2016a)
Eastern Asia	1981–2009	Negative	Yield trend at Toncheng early rice: 30 kg ha^{-1} yr^{-1} or 0.74% yr^{-1}.	Temperature/ solar radiation/ precipitation	High	Zhang et al. (2016a)
Eastern Asia	1981–2009	Negative	Year trend at Tongcheng late rice: 85 kg ha^{-1} yr^{-1} or 1.9% yr^{-1}.	Temperature/ solar radiation/ precipitation	High	Zhang et al. (2016a)
Southern Asia	1981–2010	Neutral	Almost no significant changes.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Negative	Rice yield was reduced by 0.8% during the period. Impacts were significant in 88% of the harvested areas.	Temperature/ precipitation	High	Ray et al. (2019a)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Southeastern Asia	1981–2010	Neutral	No significant changes.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Western Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1981–2010	Neutral	Mostly non-significant changes.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1974–2008	Positive	Rice yield was increased by 4.1% during the period.	Temperature/ precipitation	High	Ray et al. (2019a)
Central and South America	1981–2010	Neutral	Some positive effects, but mostly neutral.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Central and South America	1974–2008	Neutral	Rice yield was reduced by 0.7% during the period. Impacts were significant in 87% of the harvested areas.	Temperature/ precipitation	High	Ray et al. (2019a)
Southern Europe	1981–2010	Positive	Significantly positive impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Southern Europe	1974–2008	Negative	Rice yield decreased by 3.2%.	Temperature/ precipitation	High	Ray et al. (2019a)
Northern America	1981–2010	Neutral	Mostly non-significant changes.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Northern America	1974–2008	Mixed	Overall, almost no change, but impacts were significant in 92% of the harvested area.	Temperature/ precipitation	High	Ray et al. (2019a)
Wheat						
Global	1981–2010	Negative	Crop production loss attributable to anthropogenic climate change: 13.6 B$ for wheat for 1981–2010, or 1.8% (–1.3% to 7.5%) for wheat.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Global	1974–2008	Mixed	Globally, a slight increase by 0.9%, but regionally mixed effects.	Temperature/ precipitation	High depending on regions	Ray et al. (2019a)
Northern Africa	1981–2010	Mixed	No significant changes.	CO_2/temperature/ precipitation	Low	Iizumi et al. (2018)
Northern Africa	1974–2008	positive	Wheat yield was increased by 12%.	Temperature/ precipitation	High	Ray et al. (2019a)
Sub-Saharan Africa	1974–2008	Negative	Wheat yield was decreased by 2.3%.	Temperature/ precipitation	High	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Positive	Wheat yield was increased by 4.5%.	Temperature/ precipitation	High	Ray et al. (2019a)
Eastern Asia	1981–2010	Mixed	Both positive and negative effects.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Eastern Asia	1981–2009	Mixed	Increase in yield by 1–13% in northern China but decreased by 1–10% in southern China. Effects of climatic drivers also mixed depending on the climatic zones.	Temperature/ precipitation	High	Tao et al. (2014)
Eastern Asia	1981–2009	Positive	Autonomous adaptation (longer growing degree days) increased wheat yield by 15%. Solar radiation decreased during the period.	Air temperature/ others	High	Tao et al. (2015)
Eastern Asia	1981–2009	Positive	Increase in yield by 1–13% in northern China but decreased by 1–10% in southern China. Effects of climatic drivers also mixed depending on the climatic zones.	Temperature/ precipitation	High	Tao et al. (2017)
Eastern Asia	1980–2015	Positive	10.1% yield enhancement per 1.0°C. Warming shortened days to flowering by 5.4°C without yield loss.	Temperature	High	Zheng et al. (2017)
Eastern Asia	1988–2012	Positive	De-trended wheat yield increases 34 kg ha^{-1} yr^{-1}, or 371 kg ha^{-1}°C^{-1}. Warming mitigated low temperature limitation.	Temperature	High	Zheng et al. (2016)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Eastern Asia	1980–2009	Wheat	Yield increased largely due to cultivar and management changes.	Temperature/ solar radiation/ precipitation	Low	Xiao and Tao (2014)
Eastern Asia	1980–2009	Wheat	Yield increased largely due to cultivar and management changes.	Temperature/ solar radiation/ precipitation	Low	Xiao and Tao (2014)
Eastern Asia	1980–2009	Wheat	Climate change effects were significantly negative.	Temperature/ solar radiation/ precipitation	High	Xiao and Tao (2014)
Eastern Asia	1980–2009	Wheat	Climate change effects were significantly negative.	Temperature/ solar radiation/ precipitation	High	Xiao and Tao (2014)
Eastern Asia	1981–2009	Wheat	Trends in dry stress (heat degree days, HDD) and heat stress (growing degree days, GDD) had mixed effects depending on the areas of the study. −1.28% to +0.3% yr^{-1}.	Heat stress/dry stress	High	Chen et al. (2016)
Eastern Asia	1980–2009	Wheat	For the whole country, planting-area-weighted average of yield change due to trends in mean temperature and precipitation together was about 1.16%, −0.31%, −0.40% and 0.11% over the whole period for rice, wheat, maize and soybean, respectively.	Solar radiation/ temperature/ rainfall	Medium	Zhang et al. (2016c)
Southern Asia	1981–2009	Negative	5% decrease for the whole study period. 2–4% yield reduction with a 1°C increase.	Air temperature	High	Gupta et al. (2016)
Southern Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Negative	Wheat yield was decreased by 0.9%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Western Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1990–2015	Negative	Actual yield tripled, but the water-limited yield potential declined by 27%. Negative effects of reduced rainfall and rising temperatures. Elevated CO_2 concentrations prevented a further 4% loss relative to the 1990 yields.	Rainfall/ temperature/CO_2	High	Hochman et al. (2017)
Australia and New Zealand	1981–2010	Mixed	Both positive and negative effects.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1974–2008	Negative	Wheat yield was decreased by 5.8%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central and South America	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Central and South America	1974–2008	Negative	Wheat yield was decreased by 1.6%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central and South America	1971–2012	Negative	The effect of climate trends for the whole period was −5.1% for wheat. Crop yield gains for this period could have been 15–20% higher if climate trend was not significant.	Precipitation/ temperature	High	Verón et al. (2015)
Eastern Europe	1981–2010	Neutral	Almost non-significant changes.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Eastern Europe	1974–2008	Negative	Wheat yield was decreased by 2.1%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Northern Europe	1961–2014	Positive	A largely positive effect in UK (66%).	Temperature	High	Agnolucci and De Lipsis (2020)
Northern Europe	1981–2010	Positive	At the northern border, some positive effects, but negative effects in southern stages.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Northern Europe	1989–2009	Positive	Impacts on wheat during the period. Ireland, +9.2% UK, + 3.2%	Temperature/ precipitation	High	Moore and Lobell (2015)
Northern Europe	1974–2008	Negative	Wheat yield was decreased by 2.1%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Southern Europe	1961–2014	Negative	Negative effects in Italy (–10.5%) and Spain (–6.7%). Temperature trend is responsible for a reduction in the long-run growth rate of yield in wheat.	Temperature	High	Agnolucci and De Lipsis (2020)
Southern Europe	1981–2010	Mixed	Both positive and negative effects.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Southern Europe	1989–2009	Negative	Impacts on wheat during the period. Greece, –6.9% Spain, –2.6% Italy, –16.5% Portugal, –1.4%	Temperature/ precipitation	High	Moore and Lobell (2015)
Southern Europe, Western Europe	1974–2008	Negative	Wheat was decreased by 8.7%.	Temperature/ precipitation	High	Ray et al. (2019a)
Western Europe	1961–2014	Negative	All negative for the period; Belgium (–8.9%), France (–19.2%) and Germany (–29.7%). Temperature trend is responsible for a reduction in the long-run growth rate of yield in wheat.	Temperature	High	Agnolucci and De Lipsis (2020)
Western Europe	1981–2010	Neutral	Mostly non-significant changes.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Western Europe	1989–2009	Negative	Impacts on wheat during the period. Belgium, –4.7% Germany, –0.2% France, –3.6% Luxemburg, –7.5% the Netherlands, –1.7%	Temperature/ precipitation	Medium	Moore and Lobell (2015)
Northern America	1981–2010	Negative	Mostly significantly negative effects.	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Northern America	1974–2008	Negative	Wheat yield was reduced by 1.3% during the period.	Temperature/ precipitation	High	Ray et al. (2019a)
Maize, rice, wheat						
Global	1961	Neutral	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Northern Africa	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Sub-Saharan Africa	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Western Asia	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Southeastern Asia	1961	Neutral	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Central Asia	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Eastern Asia	1961	Neutral	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Australia and New Zealand	1961	Neutral	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Latin America and the Caribbean	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Eastern Europe	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Western Europe	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Northern Europe	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Southern Europe	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Northern America	1961	Negative	A significantly positive yield trend over the period was reduced by the effects of anthropogenic climate warming.	Temperature/ precipitation	High	Moore (2020)
Barley						
Global	1974–2008	Mixed	Yield change impact was –7.9%, globally.	Temperature/ precipitation	High	Ray et al. (2019a)
Northern Africa	1974–2008	Negative	Barley yield was reduced by 6.8%.	Temperature/ precipitation	High	Ray et al. (2019a)
Sub-Saharan Africa	1974–2008	Neutral	Almost no effects on barley (–0.6%).	Temperature/ precipitation	low	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Positive	Barley yield was increased by 1.6%.	Temperature/ precipitation	High	Ray et al. (2019a)
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Negative	Barley yield was decreased by 0.9%.	Temperature/ precipitation	High	Ray et al. (2019a)
Australia and New Zealand	1974–2008	Negative	Barley yield was decreased by 2.3%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Central and South America	1974–2008	Positive	Barley yield was increased by 4.0%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Eastern Europe, Northern Europe	1974–2008	Negative	Barley yield was decreased by 9.1%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Northern Europe	1989–2009	Neutral	Impacts on barley during the period. Ireland, –0.8% UK, –0.8%	Temperature/ precipitation	High	Moore and Lobell (2015)
Southern Europe	1989–2009	Negative	Impacts on barley during the period. Greece, –8.4% Spain, –5.9% Italy, –6.8% Portugal, –2.9%	Temperature/ precipitation	High	Moore and Lobell (2015)
Southern Europe	1974–2008	Negative	Barley yield was decreased by 16.1%.	Temperature/ precipitation	High	Ray et al. (2019a)
Western Europe	1989–2009	Negative	Impacts on barley during the period. Belgium, –5.0% Germany, –3.2% France, –3.4% Luxemburg, –5.1% the Netherlands, –2.1%	Temperature/ precipitation	Medium	Moore and Lobell (2015)
Western Europe	1974–2008	Negative	Barley, –16.1%	Temperature/ precipitation	High	Ray et al. (2019a)
Northern America	1974–2008	Negative	Barely, –2.5%	Temperature/ precipitation	Medium	Ray et al. (2019a)
Sorghum, millet						
Global	1974–2008	Mixed	Yield change due to climate change. +2.1%, sorghum (% relative to the average between 1974 and 2008) Rising temperature, variable precipitation.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Northern Africa	1974–2008	Positive	Sorghum yield was increased by 17.9%.	Temperature/ precipitation	High	Ray et al. (2019a)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Sub-Saharan Africa	1974–2008	Neutral	Almost no effect on sorghum yield (0.7%).	Temperature/ precipitation	Low	Ray et al. (2019a)
Sub-Saharan Africa	1951–2010	Negative	Human-induced climate warming reduced sorghum yield by 5–15%. These losses are equivalent to 0.73–2.17 billion USD damage (sorghum). 1°C warming across West African countries and mixed changes in precipitation (from –10% to +10% depending on regions) have caused significant yield losses of two major crops.	Temperature/ extreme rainfall	High	Sultan et al. (2019)
Central Asia, Eastern Asia	1974–2008	Positive	Sorghum yield was increased by 4.9%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Neutral	Almost no effect on sorghum yield (0.9%).	Temperature/ precipitation	Low	Ray et al. (2019a)
Australia and New Zealand	1974–2008	Negative	Sorghum yield was decreased by 30.5%.	Temperature/ precipitation	High	Ray et al. (2019a)
Central and South America	1974–2008	Neutral	No effect on sorghum yield (0.0%).	Temperature/ precipitation	Medium	Ray et al. (2019a)
Eastern Europe, Northern Europe	1974–2008	Negative	Sorghum yield was decreased by 9.5%.	Temperature/ precipitation	High	Ray et al. (2019a)
Southern Europe, Western Europe	1974–2008	Negative	Sorghum yield was decreased by 18.2%.	Temperature/ precipitation	High	Ray et al. (2019a)
Northern America	1974–2008	Positive	Sorghum yield was increased by 4.3%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Sub-Saharan Africa	1951–2010	Negative	Human-induced climate warming reduced millet yield by 10–20% relative to the yields simulated under the counterfactual non-climate change data since 1850. These losses are equivalent to 2.33–4.02 billion USD damage (millet). 1°C warming across West African countries and mixed changes in precipitation (from –10% to +10% depending on regions) have caused significant yield losses of two major crops.	Temperature/ extreme rainfall	High	Sultan et al. (2019)
Soybean						
Global	1981–2010	Negative	Crop production loss attributable to anthropogenic climate change: 6.6 B$ yr^{-1} or 4.5% (0.5–8.4%).	CO_2/temperature/ changes in precipitation	High	Iizumi et al. (2018)
Global	1974–2008	Mixed	Yield change due to climate change was +3.5% globally but varied depending on regions.	Temperature/ precipitation	High	Ray et al. (2019a)
Northern Africa	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Northern Africa	1974–2008	Positive	Soybean yield was reduced by 10.9%.	Temperature/ precipitation	High	Ray et al. (2019a)
Sub-Saharan Africa	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Sub-Saharan Africa	1974–2008	Negative	Soybean yield was reduced by 1.6%.	Temperature/ precipitation	High	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Neutral	Overall effect is +0.2%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Eastern Asia	1981–2010	Mixed	Both positive and negative effects.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Eastern Asia	1980–2009	Mixed	For the whole country, planting-area-weighted average of yield change due to trends in mean temperature and precipitation together was about 1.16%, –0.31%, –0.40% and 0.11% over the whole period for rice, wheat, maize and soybean, respectively.	Solar radiation/ temperature/ rainfall	Medium	Zhang et al. (2016c)
Southern Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Negative	Soybean yield was reduced by 3.2%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Southeastern Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Western Asia	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1981–2010	Mixed	Both positive and negative effects.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Australia and New Zealand	1974–2008	Negative	Soybean yield was reduced by 6.3%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central and South America	1981–2010	Negative	Significantly negative impacts.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Central and South America	1974–2008	Positive	Soybean was reduced by 5.4%.	Temperature/ precipitation	High	Ray et al. (2019a)
Central and South America	1971–2012	Negative	The effect of climate trends for the whole period was –2.6%. Crop yield gains for this period could have been 15–20% higher if climate trend was not significant.	Precipitation/ temperature	High	Verón et al. (2015)
Eastern Europe	1981–2010	Neutral	Almost non-significant changes.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Eastern Europe, Northern Europe	1974–2008	Negative	Soybean yield was reduced by 3.8%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Southern Europe, Western Europe	1974–2008	Negative	Soybean yield was reduced by 21.2%.	Temperature/ precipitation	High	Ray et al. (2019a)
Western Europe	1981–2010	Positive	At the northern border, some positive effects, but negative effects in southern stages.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Northern America	1981–2010	Mixed	At the northern border, some positive effects, but negative effects in southern stages.	CO_2/temperature/ precipitation	High	Iizumi et al. (2018)
Northern America	1974–2008	Positive	Soybean was increased by 3.3%.	Temperature/ precipitation	High	Ray et al. (2019a)
Oil palm						
Global	1974–2008	Negative	Yield change due to climate change was –13.4%	Temperature/ precipitation	High	Ray et al. (2019a)
Sub-Saharan Africa	1974–2008	Neutral	Yield change due to climate change was 0%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Negative	Yield change due to climate change was –0.4%.	Temperature/ precipitation	High	Ray et al. (2019a)
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Negative	Yield change due to climate change was –15.9%	Temperature/ precipitation	High	Ray et al. (2019a)
Central and South America	1974–2008	Neutral	Yield change due to climate change was –0.6%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Northern America	1974–2008	Negative	Yield change due to climate change was –7.2%.	Temperature/ precipitation	High	Ray et al. (2019a)
Sugarcane						
Global	1974–2008	Mixed	Yield change due to climate change was +1.0%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Northern Africa	1974–2008	Negative	Yield change due to climate change was –5.1%.	Temperature/ precipitation	High	Ray et al. (2019a)
Sub-Saharan Africa	1974–2008	Negative	Yield change due to climate change was –3.9%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Positive	Yield change due to climate change was +5.3%.	Temperature/ precipitation	High	Ray et al. (2019a)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Neutral	Yield change due to climate change was –0.6%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Australia and New Zealand	1974–2008	Neutral	Yield change due to climate change was 0.4%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Central and South America	1974–2008	Positive	Yield change due to climate change was +2.5%.	Temperature/ precipitation	High	Ray et al. (2019a)
Southern Europe, Western Europe	1974–2008	Negative	Yield change due to climate change was +2.7%.	Temperature/ precipitation	High	Ray et al. (2019a)
Northern America	1974–2008	Positive	Yield change due to climate change was +1.7%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Sugar beet						
Northern Europe	1989–2009	Positive	Impacts on barley during the period. Ireland, 0% UK, 5%	Temperature/ precipitation	High	Moore and Lobell (2015)
Southern Europe	1989–2009	Negative	Impacts on sugar beet during the period. Greece, –9.8% Spain, 0.0% Italy, –12.6%	Temperature/ precipitation	High	Moore and Lobell (2015)
Western Europe	1989–2009	Positive	Impacts on sugar beet during the period. Belgium, 2.3% Germany, 2.6% France, 2.4% the Netherlands, 1.1%	Temperature/ precipitation	Medium	Moore and Lobell (2015)
Production, cassava						
Global	1974–2008	Mixed	Yield change due to climate change was –0.5%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Northern Africa	1974–2008	Positive	Yield change due to climate change was +18.0%.	Temperature/ precipitation	High	Ray et al. (2019a)
Sub-Saharan Africa	1974–2008	Neutral	Yield change due to climate change was +1.7%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Neutral	Yield change due to climate change was +1.2%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Southern Asia, Southeastern Asia, Western Asia	1974–2008	Negative	Yield change due to climate change was –5.6%.	Temperature/ precipitation	High	Ray et al. (2019a)
Central and South America	1974–2008	Neutral	Yield change due to climate change was +0.5%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Northern America	1974–2008	Negative	Yield change due to climate change was –2.9%.	Temperature/ precipitation	High	Ray et al. (2019a)
Rapeseed						
Global	1974–2008	Neutral	Yield change due to climate change was +0.5%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Sub-Saharan Africa	1974–2008	Positive	Yield change due to climate change was +24.0%.	Temperature/ precipitation	High	Ray et al. (2019a)
Southeastern Asia, Southern Asia, Western Asia	1974–2008	Positive	Yield change due to climate change was +1.9%.	Temperature/ precipitation	High	Ray et al. (2019a)
Central Asia, Eastern Asia	1974–2008	Positive	Yield change due to climate change was +5.9%.	Temperature/ precipitation	High	Ray et al. (2019a)
Australia and New Zealand	1974–2008	Neutral	Yield change due to climate change was +0.6%.	Temperature/ precipitation	Medium	Ray et al. (2019a)
Central and South America	1974–2008	Positive	Yield change due to climate change was +6.8%.	Temperature/ precipitation	High	Ray et al. (2019a)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Eastern Europe, Northern Europe	1974–2008	Positive	Yield change due to climate change was +3.1%.	Temperature/ precipitation	Low	Ray et al. (2019a)
Southern Europe, Western Europe	1974–2008	Negative	Yield change due to climate change was –11.4%.	Temperature/ precipitation	High	Ray et al. (2019a)
Cereals						
Eastern Europe	1961–2018	Negative	Composite drought and heatwave impact on cereal yields was –12.8% during the period.	Drought/heat	High	Brás et al. (2021)
Southern Europe	1961–2018	Negative	Composite drought and heatwave impact on cereal yields was 6.9% during the period	Drought/heat	High	Brás et al. (2021)
Western Europe	1961–2018	Negative	Composite drought and heatwave impact on cereal yields was –6.6%.	Drought/heat	High	Brás et al. (2021)
Non-cereals						
Eastern Europe	1961–2018	Negative	Composite drought and heatwave impact on non-cereal yields was –5.9% during the period.	Drought/heat	High	Brás et al. (2021)
Western Europe	1961–2018	Negative	Composite drought and heatwave impact on non-cereal yields was –4.5%.	Drought/heat	High	Brás et al. (2021)
Southern Europe	1961–2018	Negative	Composite drought and heatwave impact on non-cereal yields –1.6%.	Drought/heat	High	Brás et al. (2021)
Agricultural total factor productivity (TFP)						
Global	1960–2006	Mixed	Negative relations between total factor productivity and climate variable found in low-income countries, i.e., 1.1–1.8% decrease per 1°C increase.	Temperature/ precipitation	Low	Letta and Tol (2019)
Global	1961–2020	Negative	Human-induced climate change reduced TFP by 21% on average.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Northern Africa	1961–2020	Negative	Human-induced climate change reduced TFP by 30%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Sub-Saharan Africa	1961–2020	Negative	Human-induced climate change reduced TFP by 34%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Central Asia	1961–2020	Negative	Human-induced climate change reduced TFP by 0–20%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Eastern Asia	1961–2020	Negative	Human-induced climate change reduced TFP by 0–15%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Southern Asia	1961–2020	Negative	Human-induced climate change reduced TFP by 20–35%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Southeastern Asia	1961–2020	Negative	Human-induced climate change reduced TFP by 15–40%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Western Asia	1961–2020	Negative	Human-induced climate change reduced TFP by 15–35%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Australia and New Zealand	1978–2023	Negative	Agricultural TFP slowed down after 1994 (1978–2013). Weather-induced differences in patterns of technological diffusion.	Drought	Medium	Chambers et al. (2020)
Australia and New Zealand	1961–2020	Negative	Human-induced climate change reduced TFP by 15–25%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Central and South America	1961–2020	Negative	Human-induced climate change reduced TFP by 26%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Eastern Europe	1961–2020	Mixed	The effect of human-induced climate change on TFP was between –10 and +10%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Northern Europe	1961–2020	Negative	Human-induced climate change reduced TFP by 0–10%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Southern Europe	1961–2020	Negative	Human-induced climate change reduced TFP by 10–25%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Western Europe	1961–2020	Negative	Human-induced climate change reduced TFP by 5–10%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Northern America	1951–2020	Mixed	Increased variability of TFP between 1951 and 2010. Dependence of TFP on climatic variability increased from 50% in 1951–1980 to 70% in 1981–2010.	Temperature/ precipitation	Medium	Li et al. (2017)
Northern America	1961–2020	Negative	Human-induced climate change reduced TFP by 13%.	Temperature/ precipitation	High	Ortiz-Bobea et al. (2021)
Short-term weather sensitivity						
Global	1980–2010	Negative	Major climate modes affect the crop production variability. Regional breakdown below. Large-scale modes of climate variability (El Niño-Southern Oscillation, Indian Ocean Dipole, tropical Atlantic variability, and the North Atlantic Oscillation) account for 18%, 7% and 6% of global maize, soybean and wheat production variability.	Drought/heat	Low	Anderson et al. (2019)
Global	1980–2010		Weather variations explain more than 50% of the yield variability in five countries for wheat (Australia, Canada, Spain, Hungary and Romania), seven countries for maize (South Africa, Romania, France, USA, Hungary, Germany and Italy), two countries for rice (Japan and South Korea) and one country for soy (Argentina).	Precipitation/ temperature	Medium	Frieler et al. (2017)
Global	1961–2010	Negative	During 1961–2010, modelled crop productivity is significantly influenced by at least one large-scale climate oscillation in two-thirds of global cropland area. 27% of global crop production is sensitive to variations in ENSO, 5% to variations in IOD, and 20% to variations in NAO.	Climate oscillation	Medium	Heino et al. (2018)
Global	1981–2010	Negative	Year-to-year yield variability of maize, rice, wheat and soybean decreased in 19–33% of the harvested area on the globe but increased in 9–22% of the area (1981–2010). Impacts were large in major producing regions: maize and soybean in Argentina and Northeast China; rice in Indonesia and Southern China; wheat in Australia, France and Ukraine. Impacts amplified in food insecure regions: maize in Kenya and Tanzania and rice in Bangladesh and Myanmar. 21% of yield variability explained by agro-climate index. Temperature above the optimal range explained 2–10% of the variation.	Agro-climatic index estimated from temperature solar radiation and precipitation (or soil moisture)	High	Iizumi and Ramankutty (2016)
Global	1983–2009	Negative	Three-fourths of the global harvested areas (454 million hectares) experienced drought-induced yield losses over this period, and the cumulative production losses correspond to 166 billion USD. Average drought-induced yield loss produced by individual drought events from 1983 to 2009 was greater where per capita GDP is lower (in low-income countries).	Drought	Low	Kim et al. (2019)
Global	1961–2016	Negative	25% yield loss in crop yields in dry conditions (crop-country specific standardised precipitation index (SPI) < 0.8) compared with wet conditions (SPI > 0.8) between 1961 and 2016. Yield loss probability due increases by 22% for maize, 9% for rice, and 22% for soybean in drought conditions.	Drought	Medium	Leng and Hall (2019)
Global	1961–2008	Negative	Synchronisation in production within major commodities such as maize and soybean has declined in recent decades, leading to increased global stability in production of these crops. However, synchrony between crops has increased, making global calorie production more unstable.	Precipitation/ temperature	Low	Mehrabi and Ramankutty (2019)

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Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Global	1979–2008	Negative	Yield variability of the four major crops (maize, rice, wheat and soybean) in 13,500 political units of the world (1979–2008). Climate variability accounts for 32–39% of the observed yield variability.	Precipitation/ temperature	Low	Ray et al. (2015)
Global	1964–2007	Negative	National cereal production loss of 9–10% by weather extremes between 1964 and 2007. About 7% greater production losses from more recent droughts (1985–2007) than from earlier droughts (1964–1984). 8–11% greater losses in high-income countries than in low-income ones. Droughts affect both harvested areas and yields, whereas heat decreases cereal yields.	Drought/ temperature	High	Lesk et al. (2016)
Global	1980–2010	Negative	More than 50% of the world wheat production anomalies are from two major producers. Heat and drought account for 42% of the world anomalies. National breakdown follows. Heat stress over wheat cropping regions increased significantly in the period 1980–2010, especially since the mid-1990s. Excess water is a source of variation in some mid- or high latitudes like in China and India.	Heat/drought/ excess water	Medium	Zampieri et al. (2017)
Eastern Asia	1980–2009	Negative	Maize yield sensitivity to drought increased between 1980 and 2009. Gap between rainfed and irrigated maize yield widened from 5% in the 1980s to 10% in the 2000s.	Precipitation/ temperature	High	Meng et al. (2016)
Eastern Asia	1980–2008	Negative	Climate anomalies of three variables could cause up to 50% for wheat, maize and soybean of yield reductions, and ~20% reduction in rice. High temperatures were unfavourable for rice productivity in southwestern China.	Drought/heat/ others	High	Tao et al. (2016b)
Eastern Asia	1993–2011	Neutral	A 1% increase in extreme-heat-degree-days and consecutive-dry-days results in a maize yield decline of 0.2% and 0.07%, respectively, and 0.3% for cold days occurring during the growing season.	Temperature/ precipitation	Low	Wei et al. (2016)
Eastern Asia	1981–2010	Negative	Heat stress changes during the 1981–2010 period decreased yields for early rice as observed in the growth stage-specific regressions, but decreased yield of the late rice due to the cold stress changes. Extreme stresses threatened the yield of double rice system, and vapour pressure deficits changed yield by –6.66% for the early rice and –1.82% for the late rice.	Temperature/ vapour pressure deficit	Low	Liu et al. (2019b)
Eastern Asia	1980–2009	Negative	21.3% (wheat) yield reduction per °C (max T) and 8.7% (wheat) per 10% reduction of precipitation warming–drying trend (1980–2009).	Temperature/ precipitation	High	Zhang et al. (2015a)
Eastern Asia	1980–2009	Negative	28.4% (naked oat) yield reduction per °C (max T) and 11.8% (naked oat) per 10% reduction of precipitation warming–drying trend (1980–2009).	Temperature/ precipitation	High	Zhang et al. (2015a)
Eastern Asia	1980–2009	Negative	Yield anomaly analysis showed that 16.2% (potato) yield reduction per °C (max T) and 6.6% (potato) per 10% reduction of precipitation warming–drying trend (1980–2009)	Temperature/ precipitation	High	Zhang et al. (2015b)
Australia and New Zealand	1980–2012	Negative	Yield of the five most important rainfed crop estimated to have decreased by 25–45% by the severe droughts relative to the wet seasons.	Drought	Low	Madadgar et al. (2017)
Australia and New Zealand	1980–2012	Negative	Yield of the five most important rainfed crops (barley, broad beans, canola and lupine) was estimated to have decreased by 25–45% by the severe droughts relative to the wet seasons.	Drought	Low	Madadgar et al. (2017)

Sub-region	Period	Effect	Observed change in human or natural system and contribution of climate change	Climate drivers	Robustness in attribution of impact to climate change	Reference
Europe	1984–2009	Negative	Temperature accounts for 1/4 interannual yield variability of wheat and maize yield variability. Heat stress effects were not apparent except in Romania and Bulgaria. Drought explains additional 24% of the variation (46% explained by the two variables). Drought had a marginal effect on wheat, except in Spain and Romania where inclusion of drought effects account for 40–50% variation. In Slovakia, 65% of maize variation is attributable to temperature and drought. In Bulgaria and Czech, 50% of the variation is accounted for by temperature and droughts.	Temperature/ precipitation	Low	Webber et al. (2018)
Northern America	1980–2010	Negative	Maize yield change per °C of temperature anomaly became less negative from –6.9% °C^{-1} of in first half period of 1980–2010 to –2.4% to –3.5% °C^{-1} in the second half. Negative effects countered by increased water availability.	Temperature/ precipitation	High	Leng and Hall (2019)
Northern America	1995–2012	Negative	Maize yield increased during the 1995–2012 period, but sensitivity to drought increased.	Precipitation/ temperature	High	Lobell et al. (2014)
Northern America	1958–2007	Negative	Yield of maize and soybean increased in the 50-year period (1958–2007) with increasing spatial variability. Drought sensitivity of maze and soybean changed during the period between 1958 and 2007 in the US maize- and soybean-growing regions, the central and southeastern US states becoming more sensitive and the northern and western states becoming less sensitive. Drought is associated with 13% of overall yield variability.	Standardised precipitation evapotranspiration index (SPEI, difference between precipitation and evapotranspiration)	High	Zipper et al. (2016)
Northern America	1994–2013	Negative	A loss of USD 11 billion. 2.4% soybean yield reduction by 1°C increase of growing season temperature.	Temperature/ precipitation	Medium	Mourtzinis et al. (2015)
Northern America	2019	Negative	Flooding and inundation delayed planting by 16 days and reduced photosynthesis and crop productivity by 15%. Indirect effects of flooding, which affected cropping season, yield and carbon sequestration.	Flood	Low	Yin et al. (2020)
Northern America	1960–2004	Mixed	Variability of TFP increased during the 1960 and 2004 period in some states but decreased in others. TFP in the Midwest, the Southern Plains and the Southeast are particularly sensitive to high summer temperatures. TFP loss per degree increase in summer heat increased from –4.4% K^{-1} in 1960–1982 to –9.4% K^{-1} in 1983–2004 in the Midwest.	Temperature/ precipitation	Medium	Ortiz-Bobea et al. (2018)

SM5.2 Observed Impacts, Projected Impacts and Adaptation Options in Other Crops

This supplementary information provides details for:

Figure 5.3: Synthesis of literature on observed impacts of climate change on productivity by crop type and region;

Figure 5.8: Synthesis of literature on the projected impacts of climate change on different cropping systems;

Figure 5.10: Synthesis of literature on the implementation of on-farm adaptation options across different cropping systems.

Methodology

A scoping review was performed to help with the assessment of literature on other crops (other than the major crops). The aim of the review was to identify trends and gaps in the literature relating to climate change for different crop types in terms of, observed impacts (Figure 5.4), projected impacts (Figure 5.8) and adaptation options (Figure 5.10). The literature search was performed using the SCOPUS database with a base query of climate change terms combined with a crop type query defined for each crop type using FAO classifications with crop species grouped by growth habit (see details below). A full search of title, abstract and keywords was used with the time period limited to 2013–2021 (the period of this assessment cycle).

A title screen was performed to assign each article to one or more figures and to exclude misidentified papers. An abstract screen was performed to code the papers according to the categories used in each figure (see below).

Figure 5.3 Inclusion criteria for crop categories (right panel)

This figure assesses literature reporting observed impacts on crop productivity (yield, pest and disease pressure, harvest quality, etc.) that have occurred in the past. This includes attribution studies (*high confidence*), statistical associations (*medium confidence*) and studies based on perception of climate impacts by stakeholders or the judgment of experts—even where associations with climate are not assessed (*low confidence*). The combined confidence score was calculated from the individual studies (see SM5.1). The projected impacts on crop performance are reported as positive, negative or mixed. For Figure 5.3, the category 'cereals' includes the same data set as used in the left panel for wheat, maize and rice along with other cereals, while 'legumes' includes the data set for soybean along with other legume species (see SM5.1). The focal region or regions was used to further disaggregate the assessment (see below). Review papers were included where regional synthesis is provided or where primary data are reported (otherwise primary sources were used). Excluded from the search were projection studies and experimental studies (in laboratory or controlled environment settings; these studies are given consideration in the main text and are summarised elsewhere; e.g., Daryanto et al., 2017; Bisbis et al., 2018; Alae-Carew et al., 2020).

Figure 5.8 Inclusion criteria

This figure assesses literature reporting projected impacts on crop productivity (yield, pest and disease pressure, harvest quality, etc.), including all emission scenarios and time periods. The confidence for each study was coded as *low*, *medium* or *high* based on the assertions of the authors. The combined confidence score was calculated from the individual studies (see SM5.1). The projected impacts on crop performance are reported as positive, negative or mixed (mixed includes reports where different scenarios or time periods produce contrasting results). In Figure 5.8, studies on the four major crops (wheat, maize, rice and soybean) are not included. Review papers were included where regional synthesis is provided or where primary data are reported (otherwise primary sources were used). For each study, the main climate driver or drivers was used to further disaggregate the assessment (see below). The driver 'temperature' includes impacts due to daily temperature and heat stress events; 'Phenology and seasons' includes impacts due to the duration of the growing season (e.g., growing degree days, frost-free periods, etc.) and the timing of developmental events (e.g., flowering, winter chill requirements, etc.); 'Pests and diseases' includes impacts from biotic agents under the influence of climate drivers (including temperature). All projection studies are included regardless of the choice of climate drivers or modelling approach, except for studies based exclusively on projection of the growing area suitability of the crop species (see SM5.4). Projections using spatial suitability models to estimate the impacts on crops within their current growing area or to estimate the exposure of crops to pests and diseases were included. Excluded from the search were estimates from experimental studies (in laboratory or controlled environment settings; these studies are given consideration in the main text and are summarised elsewhere; e.g., Scheelbeek et al., 2018).

Figure 5.10 Inclusion criteria

This figure assesses studies on on-farm climate change adaptation by crop type and adaptation option. It includes literature where response options were field tested (*high confidence*), experimentally tested (*medium confidence*) or suggested based on stakeholder and expert judgment (*low confidence*). The combined confidence score was calculated from the individual studies (see SM5.1). In Figure 5.10, studies on the four major crops (wheat, maize, rice and soybean) are not included. Review papers were included. For each study, the main adaptation option or options was used to further disaggregate the assessment (see below). Off-farm adaptation options not focused on crop production (e.g., livelihood diversification) are considered in Figure 5.20 and Figure 5.21.

Climate change base query

({climate change} OR {climatic change} OR {climate variability} OR {climate warming} OR {global warming}) AND NOT ({emissions} OR {mitigation} OR {REDD} OR {MRV})

Crop type query: vegetable

("vegetable crop" OR artichoke* OR asparagus OR brassica* OR broccoli OR cauliflower OR cucumber OR gherkin* OR courgette OR alliace* OR celery OR leek* OR cabbage* OR onion* OR garlic* OR pumpkin OR squash OR gourd* OR bamboo OR tomato OR Lycopersicon OR *pepper* OR eggplant OR aubergine* OR "Solanum melongena" OR Chayote OR "Sechium edule" OR christophine OR okra OR "Abelmoschus esculentus" OR mushroom* OR truffle*)

Crop type query: legumes (excluding soybean; see major crops)

(legume* OR phaseolus OR pisum OR lentil* OR chickpea* OR "chick pea*" OR "Cicer arietinum" OR cowpea OR "Vigna unguiculata" OR "pigeon pea" OR pigeonpea OR peanut* OR groundnut* OR "Arachis hypogaea" OR lupin* OR vetches OR vicia OR carobs)

Crop type query: salad crops

("salad crop" OR lettuce OR chicory OR celery OR spinach OR parsley OR rocket OR "collard green" OR "cassava leaves")

Crop type query: soft fruit

(fruit* OR *berries OR strawberr* OR rasberr* OR blueberr* OR cranberr* OR gooseberr* OR melon* OR watermelon* OR pineapple* OR papaya* OR "passion fruit" OR pomegranate* OR Persimmon* OR cashewapple OR "cashew apple" OR currants OR ribes)

Crop type query: root crops

(Potato* OR "Solanum tuberosum" OR sweetpotato* OR "sweet potat*" OR "Ipomoea batatas" OR cassava OR "Manihot esculenta" OR turnip* OR carrot* OR beetroot OR radish* OR yam* OR Dioscorea OR taro* OR cocoyam* OR yautia OR onion* OR garlic OR ginger)

Crop type query: tree crops (fruit, nut and other)

("perennial fruit" OR apple* OR "Malus pumila" OR apricot* OR citrus OR orange* OR lemon* OR lime OR grapefruit* OR tangerine* OR mandarin* OR clementine* OR satsuma* OR peach* OR nectarine* OR pear OR plum* OR quince* OR sloe* OR cherr* OR avocado* OR breadfruit* OR mango* OR olive* OR "Olea europaea" OR guava* OR lyche* OR jackfruit* OR "dragon fruit*" OR "palm fruit*" OR kapok OR banana* OR plantain* OR Musa OR grape OR "kiwi fruit" OR "Vitis vinifera" OR "date palm" OR "Phoenix dactylifera" OR "common fig" OR "Ficus carica")

(almond* OR cashew* OR hazel* OR walnut* OR pistachio* OR macadamia* OR chestnut* OR Areca OR "Karite nut*" OR sheanut* OR "Vitellaria paradoxa" OR kola* OR "brazil nut" OR "Bertholletia excelsa" OR "pine nut")

OR (cocoa OR cacao OR theobroma)

Table SM5.2 | References by figure and coding category

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Lafta et al. (2017)	Field evaluation of green and red leaf lettuce genotypes in the Imperial, San Joaquin, and Salinas Valleys of California for heat tolerance and extension of the growing seasons	Leafy crops	Fig. 5.3 (Observed)	Northern America		
Gilardi et al. (2018a)	Emerging pathogens as a consequence of globalization and climate change: Leafy vegetables as a case study	Leafy crops	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Southern Europe		Agronomy, Climate services, Plant breeding
Gilardi et al. (2018b)	Emerging foliar and soil-borne pathogens of leafy vegetable crops: a possible threat to Europe	Leafy crops	Fig. 5.3 (Observed)	Southern Europe		
El-Danasoury and Iglesias-Piñeiro (2017)	Performance of the slug parasitic nematode *Phasmarhabditis hermaphrodita* under predicted conditions of winter warming	Leafy crops	Fig. 5.8 (Projection)		Pests and diseases	
Molina-Montenegro et al. (2016)	Root-endophytes improve the ecophysiological performance and production of an agricultural species under drought condition	Leafy crops	Fig. 5.10 (Adaptation)			Agroecology
Gullino et al. (2019)	Ready-to-eat salad crops: a plant pathogen's heaven	Leafy crops	Fig. 5.10 (Adaptation)			Agronomy
Sabri et al. (2019)	The use of soil cooling for growing temperate crops under tropical climate	Leafy crops	Fig. 5.10 (Adaptation)			Agronomy
Dong et al. (2018)	Effects of elevated CO_2 on nutritional quality of vegetables: a review	Leafy crops	Fig. 5.10 (Adaptation)			Agronomy, Shift crop/cultivar
Testani et al. (2020)	Agroecological practices for organic lettuce: effects on yield, nitrogen status and nitrogen utilisation efficiency	Leafy crops	Fig. 5.10 (Adaptation)			Conservation agriculture
Beacham et al. (2018)	Addressing the threat of climate change to agriculture requires improving crop resilience to short-term abiotic stress	Leafy crops	Fig. 5.10 (Adaptation)			Plant breeding
Jasper et al. (2020)	Growth temperature influences postharvest glucosinolate concentrations and hydrolysis product formation in first and second cuts of rocket salad	Leafy crops	Fig. 5.10 (Adaptation)			Plant breeding
Lafta et al. (2017)	Field evaluation of green and red leaf lettuce genotypes in the imperial, San Joaquin, and Salinas Valleys of california for heat tolerance and extension of the growing seasons	Leafy crops	Fig. 5.10 (Adaptation)			Shift crop/cultivar, Shift planting date,

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Ket et al. (2018)	Simulation of crop growth and water-saving irrigation scenarios for Lettuce: a monsoon-climate case study in Kampong Chhnang, Cambodia	Leafy crops	Fig. 5.10 (Adaptation)			Water management
Martínez-Sánchez et al., (2018))	Impact of climate change and global trends on the microbial quality of leafy greens	Leafy crops	Fig. 5.10 (Adaptation)			Water management
Madadgar et al. (2017)	Probabilistic estimates of drought impacts on agricultural production	Legumes	Fig. 5.3 (Observed)	Australia and New Zealand		
Dreccer et al. (2018)	Comparison of sensitive stages of wheat, barley, canola, chickpea and field pea to temperature and water stress across Australia	Legumes	Fig. 5.3 (Observed)	Australia and New Zealand		
Potopová et al. (2017)	The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014	Legumes	Fig. 5.3 (Observed)	Eastern Europe		
Gourdji et al. (2015)	Historical climate trends, deforestation, and maize and bean yields in Nicaragua	Legumes	Fig. 5.3 (Observed)	Latin America and the Caribbean		
Eck et al. (2020)	Influence of growing season temperature and precipitation anomalies on crop yield in the southeastern United States	Legumes	Fig. 5.3 (Observed)	Northern America		
Swe et al. (2015)	Farmers' perception of and adaptation to climate-change impacts in the dry zone of Myanmar	Legumes	Fig. 5.3 (Observed)	Southeastern Asia		
Herridge et al. (2019)	The cropping systems of the Central Dry Zone of Myanmar: productivity constraints and possible solutions	Legumes	Fig. 5.3 (Observed)	Southeastern Asia		
Hoffman et al. (2018b)	Analysis of climate signals in the crop yield record of sub-Saharan Africa	Legumes	Fig. 5.3 (Observed), Fig. 5.8 (Projection)	Sub-Saharan Africa	Temperature	
Luquet et al. (2019)	Relative importance of long-term changes in climate and land-use on the phenology and abundance of legume crop specialist and generalist aphids	Legumes	Fig. 5.3 (Observed)	Western Europe		
Praveen (2017)	Spatiotemporal analysis of projected impacts of climate change on the major C3 and C4 crop yield under representative concentration pathway 4.5: insight from the coasts of Tamil Nadu, South India	Legumes	Fig. 5.8 (Projection)		Carbon dioxide, Temperature	
Mohammed et al. (2017)	Identifying best crop management practices for chickpea (*Cicer arietinum* L.) in Northeastern Ethiopia under climate change condition	Legumes	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Carbon dioxide, Temperature, Precipitation	Water management, Shift planting date, Shift crop/cultivar
Georgopoulou et al. (2017)	Climate change impacts and adaptation options for the Greek agriculture in 2021–2050: a monetary assessment	Legumes	Fig. 5.8 (Projection), Fig. 5.11, (Adaptation)		Climate change	Water management, Shift crop/cultivar, Shift planting date
Ramirez-Cabral et al. (2019)	Suitable areas of *Phakopsora pachyrhizi*, *Spodoptera exigua*, and their host plant *Phaseolus vulgaris* are projected to reduce and shift due to climate change	Legumes	Fig. 5.8 (Projection)		Pests and Diseases	
Rao et al. (2015)	Prediction of pest scenarios of *Spodoptera litura* Fab. in peanut growing areas of India during future climate change	Legumes	Fig. 5.8 (Projection)		Pests and Diseases	
Anwar et al. (2015)	Climate change impacts on phenology and yields of five broadacre crops at four climatologically distinct locations in Australia	Legumes	Fig. 5.8 (Projection)		Phenology, Precipitation	

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Sarr et al. (2016)	Projections of peanut yields from 2011 to 2040 in senegal using classification and regression trees	Legumes	Fig. 5.8 (Projection)		Precipitation	
Awoye et al. (2017)	Dynamical-statistical projections of the climate change impact on agricultural production in Benin by means of a cross-validated linear model combined with Bayesian statistics	Legumes	Fig. 5.8 (Projection)		Temperature	
Zinyengere et al. (2014)	Local impacts of climate change and agronomic practices on dry land crops in Southern Africa	Legumes	Fig. 5.8 (Projection)		Temperature	
Bahl (2015)	Climate change and pulses: approaches to combat its impact	Legumes	Fig. 5.10 (Adaptation)			Agronomy
Daryanto et al. (2017)	Global synthesis of drought effects on cereal, legume, tuber and root crops production: a review	Legumes	Fig. 5.10 (Adaptation)			Agronomy, Shift crop/cultivar
Sanogo et al. (2017)	Participatory diagnosis and development of climate change adaptive capacity in the groundnut basin of Senegal: building a climate-smart village model	Legumes	Fig. 5.10 (Adaptation)			Climate services
Ngwira et al. (2014)	DSSAT modelling of conservation agriculture maize response to climate change in Malawi	Legumes	Fig. 5.10 (Adaptation)			Conservation agriculture
Makate et al. (2019)	Increasing resilience of smallholder farmers to climate change through multiple adoption of proven climate-smart agriculture innovations. Lessons from Southern Africa	Legumes	Fig. 5.10 (Adaptation)			Conservation agriculture, Shift crop/cultivar
Bedoussac et al. (2015)	Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review	Legumes	Fig. 5.10 (Adaptation)			On-farm diversity
Araujo et al. (2015)	Abiotic stress responses in legumes: strategies used to cope with environmental challenges	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Bhandari et al. (2017)	Temperature sensitivity of food legumes: a physiological insight	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Bohra et al. (2015)	Genetics- and genomics-based interventions for nutritional enhancement of grain legume crops: status and outlook	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Crossa et al. (2017)	Genomic selection in plant breeding: methods, models, and perspectives	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Dwivedi et al. (2018)	Using biotechnology-led approaches to uplift cereal and food legume yields in dryland environments	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Gangurde et al. (2019)	Climate-smart groundnuts for achieving high productivity and improved quality: current status, challenges, and opportunities	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Kulkarni et al. (2018)	Harnessing the potential of forage legumes, alfalfa, soybean, and cowpea for sustainable agriculture and global food security	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Sultana et al. (2014)	Abiotic stresses in major pulses: current status and strategies	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Thomas and Ougham (2014)	The stay-green trait	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Varshney (2016)	Exciting journey of 10 years from genomes to fields and markets: some success stories of genomics-assisted breeding in chickpea, pigeonpea and groundnut	Legumes	Fig. 5.10 (Adaptation)			Plant breeding

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Varshney et al. (2018)	Accelerating genetic gains in legumes for the development of prosperous smallholder agriculture: integrating genomics, phenotyping, systems modelling and agronomy	Legumes	Fig. 5.10 (Adaptation)			Plant breeding
Tongruksawattana and Wainaina (2019)	Climate shock adaptation for Kenyan maize-legume farmers: choice, complementarities and substitutions between strategies	Legumes	Fig. 5.10 (Adaptation)			Shift crop/cultivar
Marrou et al. (2014)	Assessment of irrigation scenarios to improve performances of Lingot bean (*Phaseolus vulgaris*) in southwest France	Legumes	Fig. 5.10 (Adaptation)			Water management
Salinger et al. (2020)	Unparalleled coupled ocean-atmosphere summer heatwaves in the New Zealand region: drivers, mechanisms and impacts	Root crops	Fig. 5.3 (Observed)	Australasia		
Bebber (2015)	Range-expanding pests and pathogens in a warming world	Root crops	Fig. 5.3 (Observed), Fig. 5.8 (Projection)	Central Asia, Eastern Asia, Eastern Europe, Southern Europe	Pests and Diseases	
Ray et al. (2019a)	Climate change has likely already affected global food production	Root crops	Fig. 5.3 (Observed)	Central Asia, Eastern Asia, Latin America and the Caribbean, Northern America, Northern Africa, Sub-Saharan Africa, Southern Asia, Southeastern Asia, Western Asia, Global		
Tang et al. (2016)	Comparison of the impacts of climate change on potential productivity of different staple crops in the agro-pastoral ecotone of North China	Root crops	Fig. 5.3 (Observed), Fig 5.10 (Adaptation)	Eastern Asia		Shift crop/cultivar
Tang et al. (2016)	Comparison of the impacts of climate change on potential productivity of different staple crops in the agro-pastoral ecotone of North China	Root crops	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Eastern Asia		Shift crop/cultivar
Shimoda et al. (2018)	Time series analysis of temperature and rainfall-based weather aggregation reveals significant correlations between climate turning points and potato (*Solanum tuberosum* L) yield trends in Japan	Root crops	Fig. 5.3 (Observed)	Eastern Asia		
Wang et al. (2019b)	Analysis of the spatiotemporal variability of droughts and the effects of drought on potato production in northern China	Root crops	Fig. 5.3 (Observed)	Eastern Asia		
Zhang et al. (2015a)	Adaptation to a warming-drying trend through cropping system adjustment over three decades: a case study in the northern agro-pastural ecotone of China	Root crops	Fig. 5.3 (Observed)	Eastern Asia		
Potopová et al. (2017)	The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014	Root crops	Fig. 5.3 (Observed)	Eastern Europe		
Brás et al. (2021)	Severity of drought and heatwave crop losses tripled over the last five decades in Europe	Root crops	Fig. 5.3 (Observed)	Eastern Europe, Southern Europe, Western Europe		

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Raymundo et al. (2014)	Potato, sweet potato, and yam models for climate change: a review	Root crops	Fig. 5.3 (Observed), Fig. 5.8 (Projection)	Northern Europe	Climate change	
Eck et al. (2020)	Influence of growing season temperature and precipitation anomalies on crop yield in the southeastern United States	Root crops	Fig. 5.3 (Observed)	Northern America		
Graziosi et al. (2016)	Emerging pests and diseases of South-east Asian cassava: a comprehensive evaluation of geographic priorities, management options and research needs	Root crops	Fig. 5.3 (Observed)	Southeastern Asia		
Yoshida et al. (2019)	Weather-induced economic damage to upland crops and the impact on farmer household income in Northeast Thailand	Root crops	Fig. 5.3 (Observed)	Southeastern Asia		
Shiru et al. (2019)	Changing characteristics of meteorological droughts in Nigeria during 1901–2010	Root crops	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Ebrahimi et al. (2014)	Observations on the life cycle of potato cyst nematodes, *Globodera rostochiensis* and *G. pallida*, on early potato cultivars	Root crops	Fig. 5.3 (Observed)	Western Europe		
Rana et al. (2020)	Climate change and potato productivity in Punjab—impacts and adaptation	Root crops	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Carbon dioxide, Temperature	Shift planting date
Dua et al. (2015)	Impact of climate change on potato (*Solanum tuberosum*) productivity in Bihar and relative adaptation strategies	Root crops	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Carbon dioxide, Temperature	Shift planting date, Shift crop/cultivar
Dua et al. (2018)	Climate change and potato productivity in Madhya Pradesh—impact and adaptation	Root crops	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Carbon dioxide, Temperature	Shift planting date, Shift crop/cultivar
Dua et al. (2016)	Impact of climate change on potato productivity in Uttar Pradesh and adaptation strategies	Root crops	Fig. 5.8 (Projection)		Carbon dioxide, Temperature	
Yagiz et al. (2020)	Exploration of climate change effects on shifting potato seasons, yields and water use employing NASA and national long-term weather data	Root crops	Fig. 5.8 (Projection)		Carbon dioxide, Temperature,	
Deguchi et al. (2016)	Actual and potential yield levels of potato in different production systems of Japan	Root crops	Fig. 5.8 (Projection)		Carbon dioxide, Temperature, Phenology	
Georgopoulou et al. (2017)	Climate change impacts and adaptation options for the Greek agriculture in 2021–2050: a monetary assessment	Root crops	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation),		Climate change	Water management, Shift crop/cultivar, Shift planting date
Raymundo et al. (2018)	Climate change impact on global potato production	Root crops	Fig. 5.8 (Projection)		Climate change	
Knox et al. (2016)	Meta-analysis of climate impacts and uncertainty on crop yields in Europe	Root crops	Fig. 5.8 (Projection)		Climate change	
Crespo-Pérez et al. (2015)	Changes in the distribution of multispecies pest assemblages affect levels of crop damage in warming tropical Andes	Root crops	Fig. 5.8 (Projection)		Pests and Diseases	
Ashofteh et al. (2015)	Risk analysis of water demand for agricultural crops under climate change	Root crops	Fig. 5.8 (Projection)		Precipitation	
Asante and Amuakwa-Mensah (2015)	Climate change and variability in Ghana: stocktaking	Root crops	Fig. 5.8 (Projection)		Temperature	
MA et al. (2019)	Spatial distribution of crop climatic potential productivity and its response to climate change in agro-pastural ecotone in northern Shanxi province	Root crops	Fig. 5.8 (Projection)		Temperature, Precipitation	

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Markou et al. (2020)	Addressing climate change impacts on agriculture: adaptation measures for six crops in Cyprus	Root crops	Fig. 5.10 (Adaptation)			Agronomy, Climate services, On-farm diversity, Plant breeding, Water management, Shift crop/cultivar, Shift planting date
Larbi et al. (2019)	Analysis of food crops farmers' choice of climate change adaptation strategies in Kwara State, Nigeria	Root crops	Fig. 5.10 (Adaptation)			Agronomy, Climate services, Shift crop/cultivar, Shift planting date
de Araújo Visses et al. (2018)	Yield gap of cassava crop as a measure of food security—an example for the main Brazilian producing regions	Root crops	Fig. 5.10 (Adaptation)			Agronomy, Conservation agriculture, Water management, Shift crop/cultivar, Shift planting date
Mubarak (2020)	Improving water productivity and yield onion crop by combining early planting and straw mulch under different irrigation levels in dry Mediterranean region	Root crops	Fig. 5.10 (Adaptation)			Agronomy, Water management, Shift planting date
Adamides et al. (2020)	Smart farming techniques for climate change adaptation in Cyprus	Root crops	Fig. 5.10 (Adaptation)			Climate services, Water management
Manuel et al. (2019)	Parental value for tuber yield in potato under high temperature environments in climate change conditions	Root crops	Fig. 5.10 (Adaptation)			Plant breeding
Nguyen-Sy et al. (2019)	Impacts of climatic and varietal changes on phenology and yield components in rice production in Shonai region of Yamagata Prefecture, Northeast Japan for 36 years	Root crops	Fig. 5.10 (Adaptation)			Shift crop/cultivar
Tsuji et al. (2019)	Enhancing food security in subarctic canada in the context of climate change: the harmonization of indigenous harvesting pursuits and agroforestry activities to form a sustainable import-substitution strategy	Root crops	Fig. 5.10 (Adaptation)			Shift planting area
Lee and Dang (2020)	Crop calendar shift as a climate change adaptation solution for cassava cultivation area of Binh Thuan province, Vietnam	Root crops	Fig. 5.10 (Adaptation)			Shift planting date
Wang et al. (2015a)	Adaptation of potato production to climate change by optimizing sowing date in the Loess Plateau of central Gansu, China	Root crops	Fig. 5.10 (Adaptation)			Shift planting date
Li et al. (2019c)	Coupling impacts of planting date and cultivar on potato yield	Root crops	Fig. 5.10 (Adaptation)			Shift planting date
Goswami et al. (2018)	Impact assessment of climate change on potato productivity in Assam using SUBSTOR-Potato model	Root crops	Fig. 5.10 (Adaptation)			Shift planting date
Maho et al. (2019)	Changes in potato cultivation technology in Korça region as adaptation to climate change	Root crops	Fig. 5.10 (Adaptation)			Shift planting date
Srivastava et al. (2019)	Quantitative approaches in adaptation strategies to cope with increased temperatures following climate change in potato crop	Root crops	Fig. 5.10 (Adaptation)			Shift planting date
Dalias et al. (2019)	Adjustment of irrigation schedules as a strategy to mitigate climate change impacts on agriculture in cyprus	Root crops	Fig. 5.10 (Adaptation)			Water management
Brás et al. (2021)	Severity of drought and heatwave crop losses tripled over the last five decades in Europe	Soft fruit	Fig. 5.3 (Observed)	Eastern Europe, Southern Europe, Western Europe		

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Olivares (2018)	Tropical rainfall conditions in rainfed agriculture in Carabobo, Venezuela	Soft fruit	Fig. 5.3 (Observed)	Latin America and the Caribbean		
Silva and Noda (2016)	A Dinâmica entre as águas e terras na Amazônia e seus efeitos sobre as várzeas	Soft fruit	Fig. 5.3 (Observed)	Latin America and the Caribbean		
Drummond et al. (2017)	A natural history of change in native bees associated with lowbush blueberry in Maine	Soft fruit	Fig. 5.3 (Observed), Fig. 5.10 Adaptation	Northern America		On-farm diversity
Ellwood et al. (2014)	Cranberry flowering times and climate change in southern Massachusetts	Soft fruit	Fig. 5.3 (Observed)	Northern America		
Hupp et al. (2015)	How are your berries? Perspectives of Alaska's environmental managers on trends in wild berry abundance	Soft fruit	Fig. 5.3 (Observed)	Northern America		
Samtani et al. (2019)	The status and future of the strawberry industry in the United States	Soft fruit	Fig. 5.3 (Observed)	Northern America		
Andersen et al. (2017)	Impact of seasonal warming on overwintering and spring phenology of blackcurrant	Soft fruit	Fig. 5.3 (Observed)	Northern Europe		
Boulanger-Lapointe et al. (2017)	Climate and herbivore influence on *Vaccinium myrtillus* over the last 40 years in northwest Lapland, Finland	Soft fruit	Fig. 5.3 (Observed)	Northern Europe		
Sønsteby and Heide (2014)	Chilling requirements of contrasting black currant (*Ribes nigrum* L.) cultivars and the induction of secondary bud dormancy	Soft fruit	Fig. 5.3 (Observed)	Northern Europe		
Ramlall (2014)	Gauging the impact of climate change on food crops production in Mauritius: an econometric approach	Soft fruit	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Williams et al. (2017)	Impact of climate variability on pineapple production in Ghana	Soft fruit	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Vitasse et al. (2018)	Increase in the risk of exposure of forest and fruit trees to spring frosts at higher elevations in Switzerland over the last four decades	Soft fruit	Fig. 5.3 (Observed)	Western Europe		
Menzel et al. (2020)	Climate change fingerprints in recent European plant phenology	Soft fruit	Fig. 5.3 (Observed), Fig. 5.10 Adaptation	Western Europe		Shift planting date
Kabir et al. (2018)	Bio-economic evaluation of cropping systems for saline coastal Bangladesh: I. Biophysical simulation in historical and future environments	Soft fruit	Fig. 5.8 (Projection)		Climate change	
Bezerra et al. (2019)	Agricultural area losses and pollinator mismatch due to climate changes endanger passion fruit production in the Neotropics	Soft fruit	Fig. 5.8 (Projection)		Ecosystem services	
Lee et al. (2018)	Effects of climate change on the phenology of *Osmia cornifrons*: implications for population management	Soft fruit	Fig. 5.8 (Projection)		Ecosystem services	
Sridhar et al. (2017)	CLIMEX modelling for risk assessment of Asian fruit fly, *Bactrocera papayae* (Drew and Hancock, 1994) in India	Soft fruit	Fig. 5.8 (Projection)		Pests and Diseases	
Sultana et al. (2020)	Impacts of climate change on high priority fruit fly species in Australia	Soft fruit	Fig. 5.8 (Projection)		Pests and Diseases	
Hong et al., 2019	Risk map for the range expansion of *Thrips palmi* in Korea under climate change: combining species distribution models with land-use change	Soft fruit	Fig. 5.8 (Projection)		Pests and Diseases	
Bieniek et al. (2016)	Assesment of climatic conditions for *Actinidia arguta* cultivation in North-Eastern Poland	Soft fruit	Fig. 5.8 (Projection)		Phenology	

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Hidaka et al. (2017)	Crown-cooling treatment induces earlier flower bud differentiation of strawberry under high air temperatures	Soft fruit	Fig. 5.10 (Adaptation)			Agronomy
Retamal-Salgado et al. (2017)	Decrease in artificial radiation with netting reduces stress and improves rabbit-eye blueberry (*Vaccinium virgatum aiton*) 'ochlockonee' productivity	Soft fruit	Fig. 5.10 (Adaptation)			Agronomy
Wuepper et al. (2020)	Non-cognitive skills and climate change adaptation: empirical evidence from Ghana's pineapple farmers	Soft fruit	Fig. 5.10 (Adaptation)			Agronomy
Joshi and Chauhan (2016)	Combating climate change through off-seasonally raising seedling of papaya (*Carica papaya* L.) in protected environment	Soft fruit	Fig. 5.10 (Adaptation)			Agronomy
Daigle et al. (2019)	Traditional lifeways and storytelling: tools for adaptation and resilience to ecosystem change	Soft fruit	Fig. 5.10 (Adaptation)			Agronomy
Mubiru et al. (2018)	Climate trends, risks and coping strategies in smallholder farming systems in Uganda	Soft fruit	Fig. 5.10 (Adaptation)			Agronomy, Shift crop/cultivar
Jones et al. (2015)	Chilling requirement of ribes cultivars	Soft fruit	Fig. 5.10 (Adaptation)			Climate services
Guo et al. (2019)	Optimal allocation of irrigation water resources based on meteorological factor under uncertainty	Soft fruit	Fig. 5.10 (Adaptation)			Climate services
Lima et al. (2017)	Productivity and quality of melon cultivated in a protected environment under different soil managements	Soft fruit	Fig. 5.10 (Adaptation)			Conservation agriculture
Sobol et al. (2014)	Genetic variation in yield under hot ambient temperatures spotlights a role for cytokinin in protection of developing floral primordia	Soft fruit	Fig. 5.10 (Adaptation)			Plant breeding
Winde et al. (2017)	Variation in freezing tolerance, water content and carbohydrate metabolism of floral buds during deacclimation of contrasting blackcurrant cultivars	Soft fruit	Fig. 5.10 (Adaptation)			Plant breeding
Urtasun et al. (2020)	Dormancy release, germination and ex situ conservation of the southern highland papaya (*Vasconcellea quercifolia*, Caricaceae), a wild crop relative	Soft fruit	Fig. 5.10 (Adaptation)			Plant breeding
Ngo et al. (2017)	Adapting the melon production model to climate change in Giao Thuy District, Nam Dinh Province, Vietnam	Soft fruit	Fig. 5.10 (Adaptation)			Plant breeding
Ferus et al. (2017)	Hooker's or warty barberry? Physiological background analysis for choosing the right one into ornamental plantations endangered by drought	Soft fruit	Fig. 5.10 (Adaptation)			Plant breeding
Bolaños-Villegas (2020)	Chromosome engineering in tropical cash crops	Soft fruit	Fig. 5.10 (Adaptation)			Plant breeding
Adak et al. (2018)	Yield, quality and biochemical properties of various strawberry cultivars under water stress	Soft fruit	Fig. 5.10 (Adaptation)			Plant breeding, Shift crop/cultivar
Stewart (2015)	Agave as a model CAM crop system for a warming and drying world	Soft fruit	Fig. 5.10 (Adaptation)			Shift crop/cultivar
Trivedi et al. (2015)	Variability in morpho-physiological traits and antioxidant potential of kiwifruit (*Actinidia chinensis* Planch) in Central Himalayan Region	Soft fruit	Fig. 5.10 (Adaptation)			Shift crop/cultivar
Iqbal et al. (2020)	Cactus pear: a weed of dry-lands for supplementing food security under changing climate	Soft fruit	Fig. 5.10 (Adaptation)			Shift crop/cultivar

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
de Lima et al. (2015)	Partial rootzone drying (PRD) and regulated deficit irrigation (RDI) effects on stomatal conductance, growth, photosynthetic capacity, and water-use efficiency of papaya	Soft fruit	Fig. 5.10 (Adaptation)			Water management
Morris et al. (2017)	Essential irrigation and the economics of strawberries in a temperate climate	Soft fruit	Fig. 5.10 (Adaptation)			Water management
Yu et al. (2020)	Global synthesis of the impact of droughts on crops' water-use efficiency (WUE): towards both high WUE and productivity	Soft fruit	Fig. 5.10 (Adaptation)			Water management, Shift crop/cultivar
Jarvis et al. (2017)	Relationship between viticultural climatic indices and grape maturity in Australia	Tree fruits and nuts	Fig. 5.3 (Observed)	Australia and New Zealand		
Zhang et al. (2015c)	Environmental factors and seasonality affect the concentration of rotundone in *Vitis vinifera* L. cv. Shiraz wine	Tree fruits and nuts	Fig. 5.3 (Observed)	Australia and New Zealand		
Wypych et al. (2017)	Variability of growing degree days in Poland in response to ongoing climate changes in Europe	Tree fruits and nuts	Fig. 5.3 (Observed)	Eastern Europe		
Gitea et al., 2019)	Orchard management under the effects of climate change: implications for apple, plum, and almond growing	Tree fruits and nuts	Fig. 5.3 (Observed)	Eastern Europe		
Brás et al. (2021)	Severity of drought and heatwave crop losses tripled over the last five decades in Europe	Tree fruits and nuts	Fig. 5.3 (Observed)	Eastern Europe, Southern Europe, Western Europe		
Reineke and Thiéry (2016)	Grapevine insect pests and their natural enemies in the age of global warming	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Global		Agronomy, Climate services
Mozell and Thach (2014)	The impact of climate change on the global wine industry: challenges & solutions	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Global		Agronomy, Conservation agriculture, On-farm diversity, Water management, Shift crop/cultivar, Shift planting area
Legave et al. (2015)	Differentiated responses of apple tree floral phenology to global warming in contrasting climatic regions	Tree fruits and nuts	Fig. 5.3 (Observed)	Global		
Ramírez and Kallarackal (2015)	Responses of fruit trees to global climate change.	Tree fruits and nuts	Fig. 5.3 (Observed)	Global		
Jacobi et al. (2015a)	Agroecosystem resilience and farmers' perceptions of climate change impacts on cocoa farms in Alto Beni, Bolivia	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Latin America and the Caribbean		Agroecology
Jacobi et al. (2017a)	Building farm resilience in a changing climate: challenges, potentials, and ways forward for smallholder cocoa production in Bolivia	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Latin America and the Caribbean		Agroecology
Rhiney et al. (2016)	Assessing the vulnerability of Caribbean farmers to climate change impacts: a comparative study of cocoa farmers in Jamaica and Trinidad	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Latin America and the Caribbean		Plant breeding
Benmoussa et al. (2017)	Chilling and heat requirements for local and foreign almond (*Prunus dulcis* Mill.) cultivars in a warm Mediterranean location based on 30 years of phenology records	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	North Africa		Shift crop/cultivar
Ortega-Beltran et al. (2019)	Atoxigenic *Aspergillus flavus* isolates endemic to almond, fig, and pistachio orchards in California with potential to reduce aflatoxin contamination in these crops	Tree fruits and nuts	Fig. 5.3 (Observed)	North America		

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Pope et al. (2015)	Nut crop yield records show that budbreak-based chilling requirements may not reflect yield decline chill thresholds	Tree fruits and nuts	Fig. 5.3 (Observed)	North America		
Rayne and Forest (2016)	Rapidly changing climatic conditions for wine grape growing in the Okanagan Valley region of British Columbia, Canada	Tree fruits and nuts	Fig. 5.3 (Observed)	Northern America		
Ugolini et al. (2014)	Ecophysiological responses and vulnerability to other pathologies in European chestnut coppices, heavily infested by the Asian chestnut gall wasp	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Southern Europe		Climate services
Rabadán et al. (2019)	A comparison of the effect of genotype and weather conditions on the nutritional composition of most important commercial nuts	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Southern Europe		Shift crop/cultivar
Gentilucci et al. (2020)	Temperature variations in Central Italy (Marche region) and effects on wine grape production	Tree fruits and nuts	Fig. 5.3 (Observed)	Southern Europe		
Pulko (2014)	Trends in climate parameters affecting winegrape ripening in northeastern Slovenia	Tree fruits and nuts	Fig. 5.3 (Observed)	Southern Europe		
Menapace et al. (2015)	Climate change beliefs and perceptions of agricultural risks: an application of the exchangeability method	Tree fruits and nuts	Fig. 5.3 (Observed)	Southern Europe		
Paterson et al. (2018)	Predominant mycotoxins, mycotoxigenic fungi and climate change related to wine	Tree fruits and nuts	Fig. 5.3 (Observed)	Southern Europe		
Bonsignore et al. (2019)	Environmental thermal levels affect the phenological relationships between the chestnut gall wasp and its parasitoids	Tree fruits and nuts	Fig. 5.3 (Observed)	Southern Europe		
El Yaacoubi et al. (2014)	Global warming impact on floral phenology of fruit trees species in Mediterranean region	Tree fruits and nuts	Fig. 5.3 (Observed)	Southern Europe, North Africa		
Spinoni et al. (2015)	European degree-day climatologies and trends for the period 1951–2011	Tree fruits and nuts	Fig. 5.3 (Observed)	Southern Europe, Western Europe		
Fonta et al. (2018)	A Ricardian valuation of the impact of climate change on Nigerian cocoa production: insight for adaptation policy	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)	Sub-Saharan Africa	Temperature, Precipitation	Agronomy
Ameyaw et al. (2018)	Cocoa and climate change: insights from smallholder cocoa producers in Ghana regarding challenges in implementing climate change mitigation strategies	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Sub-Saharan Africa		Agroecology
Gnonlonfoun et al. (2019)	New indicators of vulnerability and resilience of agroforestry systems to climate change in West Africa: West African agroforestry systems and climate change	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Sub-Saharan Africa		Agroecology
Lahive et al. (2019)	The physiological responses of cacao to the environment and the implications for climate change resilience. A review	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Sub-Saharan Africa		Agroecology
Ofori-Boateng et al. (2015)	Climate conditions and cocoa yields in ECOWAS countries: fully modified OLS approach	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Sub-Saharan Africa		Agronomy
Oyekale (2015)	Climate change induced occupational stress and reported morbidity among cocoa farmers in South-Western Nigeria	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Sub-Saharan Africa		Climate services
Asante et al. (2016)	Farmers' perspectives on climate change manifestations in smallholder cocoa farms and shifts in cropping systems in the forest-savannah transitional zone of Ghana	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Sub-Saharan Africa		Shift crop/cultivar

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Adebisi-Adelani (2016)	Citrus and tomatoes response to climate change: survey of farmers' perception and adaptation strategies in northern Nigeria	Tree fruits and nuts	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Ofori-Boateng and Insah (2014)	The impact of climate change on cocoa production in West Africa	Tree fruits and nuts	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Ruf et al. (2015)	Climate change, cocoa migrations and deforestation in West Africa: what does the past tell us about the future?	Tree fruits and nuts	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Korres et al. (2016)	Cultivars to face climate change effects on crops and weeds: a review	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Western Europe		Shift crop/cultivar
de Cortazar Atauri et al. (2017)	Grapevine phenology in France: from past observations to future evolutions in the context of climate change	Tree fruits and nuts	Fig. 5.3 (Observed), Fig. 5.10 (Adaptation)	Western Europe		Shift crop/cultivar, Shift planting area
Cook and Wolkovich (2016)	Climate change decouples drought from early wine grape harvests in France	Tree fruits and nuts	Fig. 5.3 (Observed)	Western Europe		
Georgopoulou et al. (2017)	Climate change impacts and adaptation options for the Greek agriculture in 2021–2050: a monetary assessment	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation),		Climate change	Agronomy, Shift crop/cultivar, Water management
Giannini et al. (2017)	Projected climate change threatens pollinators and crop production in Brazil	Tree fruits and nuts	Fig. 5.8 (Projection)		Ecosystem services	
Ortega Andrade et al. (2017)	Climate change and the risk of spread of the fungus from the high mortality of *Theobroma cacao* in Latin America	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Pests and Diseases	Climate services
Aidoo et al. (2019)	Distribution, degree of damage and risk of spread of *Trioza erytreae* (Hemiptera: Triozidae) in Kenya	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Pests and Diseases	Climate services
Choudhary et al. (2019c)	Spatio-temporal temperature variations in MarkSim multimodel data and their impact on voltinism of fruit fly, *Bactrocera* species on mango	Tree fruits and nuts	Fig. 5.8 (Projection)		Pests and Diseases	
Bosso et al. (2016)	Shedding light on the effects of climate change on the potential distribution of *Xylella fastidiosa* in the Mediterranean basin	Tree fruits and nuts	Fig. 5.8 (Projection)		Pests and Diseases	
Launay et al. (2014)	Climatic indicators for crop infection risk: application to climate change impacts on five major foliar fungal diseases in Northern France	Tree fruits and nuts	Fig. 5.8 (Projection)		Pests and Diseases	
Shabani et al. (2014)	Future distributions of *Fusarium oxysporum* f. spp. in European, Middle Eastern and North African agricultural regions under climate change	Tree fruits and nuts	Fig. 5.8 (Projection)		Pests and Diseases	
Choudhary et al. (2019a)	Predicting impact of climate change on habitat suitability of guava fruit fly, *Bactrocera correcta* (Bezzi) using MaxEnt modeling in India	Tree fruits and nuts	Fig. 5.8 (Projection)		Pests and Diseases	
Choudhary et al. (2019b)	Predicting the invasion potential of indigenous restricted mango fruit borer, *Citripestis eutraphera* (Lepidoptera: Pyralidae) in India based on MaxEnt modelling	Tree fruits and nuts	Fig. 5.8 (Projection)		Pests and Diseases	
Molitor and Junk (2019)	Climate change is implicating a two-fold impact on air temperature increase in the ripening period under the conditions of the Luxembourgish grapegrowing region	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Phenology	Climate services
Vahdati et al. (2019)	Applying the AOGCM-AR5 models to the assessments of land suitability for walnut cultivation in response to climate change: a case study of Iran	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Phenology	Climate services, Shift planting area

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Parker and Abatzoglou (2018)	Shifts in the thermal niche of almond under climate change	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation),		Phenology	Shift planting area
Funes et al. (2016)	Future climate change impacts on apple flowering date in a Mediterranean subbasin	Tree fruits and nuts	Fig. 5.8 (Projection)		Phenology	
Fraga et al. (2019)	Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: a multi-model assessment	Tree fruits and nuts	Fig. 5.8 (Projection)		Phenology	
Molitor et al. (2014)	Late frost damage risk for viticulture under future climate conditions: a case study for the Luxembourgish winegrowing region	Tree fruits and nuts	Fig. 5.8 (Projection)		Phenology	
Gabaldón-Leal et al. (2017)	Impact of changes in mean and extreme temperatures caused by climate change on olive flowering in southern Spain	Tree fruits and nuts	Fig. 5.8 (Projection)		Phenology, Temperature	
Valverde et al. (2015)	Climate change impacts on rainfed agriculture in the Guadiana river basin (Portugal)	Tree fruits and nuts	Fig. 5.8 (Projection)		Precipitation	
Teslić et al. (2019)	Future climatic suitability of the Emilia-Romagna (Italy) region for grape production	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Temperature	Climate services, Shift planting area
Li et al. (2020)	Possible impact of climate change on apple yield in Northwest China	Tree fruits and nuts	Fig. 5.8 (Projection)		Temperature	
Santos et al. (2017)	Climate change impacts on thermal growing conditions of main fruit species in Portugal	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Temperature, Phenology	Shift planting area
Benmoussa et al. (2018)	Climate change threatens central Tunisian nut orchards	Tree fruits and nuts	Fig. 5.8 (Projection)		Temperature, Phenology	
Schroth et al. (2016)	Vulnerability to climate change of cocoa in West Africa: patterns, opportunities and limits to adaptation	Tree fruits and nuts	Fig. 5.8 (Projection), Fig. 5.10 (Adaptation)		Temperature, Precipitation	Agroecology
Asante and Amuakwa-Mensah (2015)	Climate change and variability in Ghana: stocktaking	Tree fruits and nuts	Fig. 5.8 (Projection)		Temperature, Precipitation	
Migliore et al. (2019)	A Ricardian analysis of the impact of climate change on permanent crops in a Mediterranean region	Tree fruits and nuts	Fig. 5.8 (Projection)		Temperature, Precipitation	
Bouregaa (2019)	Impact of climate change on yield and water requirement of rainfed crops in the Setif region	Tree fruits and nuts	Fig. 5.8 (Projection)		Temperature, Precipitation	
Abdulai et al. (2018a)	Characterization of cocoa production, income diversification and shade tree management along a climate gradient in Ghana	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Abdulai et al. (2018a)	Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Blaser et al. (2018)	Climate-smart sustainable agriculture in low-to-intermediate shade agroforests	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
de Sousa et al. (2019)	The future of coffee and cocoa agroforestry in a warmer Mesoamerica	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Jadán et al. (2015)	Influence of tree cover on diversity, carbon sequestration and productivity of cocoa systems in the Ecuadorian Amazon	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Santhyami et al. (2018)	The comparison of aboveground C-stock between cocoa-based agroforestry system and cocoa monoculture practice in West Sumatra, Indonesia	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Sonwa et al. (2019)	Structure of cocoa farming systems in West and Central Africa: a review	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Tondoh et al. (2015)	Ecological changes induced by full-sun cocoa farming in Côte d'Ivoire	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Utomo et al. (2016)	Environmental performance of cocoa production from monoculture and agroforestry systems in Indonesia	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
van der Wolf et al. (2019)	Turning local knowledge on agroforestry into an online decision-support tool for tree selection in smallholders' farms	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Ranjitkar et al. (2016a)	Climate modelling for agroforestry species selection in Yunnan Province, China	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Guillot et al. (2019)	With or without trees: resistance and resilience of soil microbial communities to drought and heat stress in a Mediterranean agroforestry system	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Naughton et al. (2015)	Land suitability modeling of shea (*Vitellaria paradoxa*) distribution across sub-Saharan Africa	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Ranjitkar et al. (2016a)	Climate modelling for agroforestry species selection in Yunnan Province, China	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology
Bandanaa et al. (2016)	Cocoa farming households in Ghana consider organic practices as climate smart and livelihoods enhancer	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology, On-farm diversity
Jacobi et al. (2015b)	Farm resilience in organic and nonorganic cocoa farming systems in Alto Beni, Bolivia	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology, On-farm diversity
Toledo-Hernández et al. (2017)	Neglected pollinators: can enhanced pollination services improve cocoa yields? A review	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology, On-farm diversity
Torres et al. (2015)	The contribution of traditional agroforestry to climate change adaptation in the Ecuadorian Amazon: the chakra system	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agroecology, On-farm diversity
Gatti et al. (2016)	Phenology, canopy aging and seasonal carbon balance as related to delayed winter pruning of *Vitis vinifera* L. cv. sangiovese grapevines	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agronomy
Petrie et al. (2017)	Pruning after budburst to delay and spread grape maturity	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agronomy
Poni et al. (2018)	Grapevine quality: a multiple choice issue	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agronomy
Tóth and Végvári (2016)	Future of winegrape growing regions in Europe	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agronomy, Climate services, Shift crop/ cultivar
Mosedale et al. (2016)	Climate change impacts and adaptive strategies: lessons from the grapevine	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agronomy, Shift crop/cultivar, Shift planting area
Van Leeuwen and Destrac-Irvine (2017)	Modified grape composition under climate change conditions requires adaptations in the vineyard	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Agronomy, Shift crop/cultivar, Shift planting area
Díez-Palet et al. (2019)	Blooming under Mediterranean climate: estimating cultivar-specific chill and heat requirements of almond and apple trees using a statistical approach	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Climate services
Zhu et al. (2016)	A model-based assessment of adaptation options for Chianti wine production in Tuscany (Italy) under climate change	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Climate services

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Alfieri et al. (2019)	Adaptability of global olive cultivars to water availability under future Mediterranean climate	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Climate services
Biasi et al. (2019)	Assessing impacts of climate change on phenology and quality traits of *Vitis vinifera* L.: the contribution of local knowledge	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Climate services, Shift crop/cultivar
Eitzinger et al. (2014)	Implications of a changing climate on food security and smallholders' livelihoods in Bogotá, Colombia	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Climate services, Shift planting area, Shift crop/cultivar
Drappier et al. (2019)	Relationship between wine composition and temperature: impact on Bordeaux wine typicity in the context of global warming—review	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Clmate services
Ponti et al. (2014)	Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Conservation agriculture
Clough et al. (2017)	Services and disservices of ant communities in tropical cacao and coffee agroforestry systems	Tree fruits and nuts	Fig. 5.10 (Adaptation)			On-farm diversity
Jacobi et al. (2017b)	Whose knowledge, whose development? Use and role of local and external knowledge in agroforestry projects in Bolivia	Tree fruits and nuts	Fig. 5.10 (Adaptation)			On-farm diversity
Vera V et al. (2019)	Biodiversity, dynamics, and impact of chakras on the Ecuadorian Amazon	Tree fruits and nuts	Fig. 5.10 (Adaptation)			On-farm diversity
Luciani et al. (2019)	Mitigation of multiple summer stresses on hazelnut (*Corylus avellana* L.): effects of the new arbuscular mycorrhiza *Glomus iranicum tenuihypharum* sp. *nova*	Tree fruits and nuts	Fig. 5.10 (Adaptation)			On-farm diversity
Balasimha (2016)	Cocoa and cashew	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Farrell et al. (2018)	Climate adaptation in a minor crop species: is the cocoa breeding network prepared for climate change?	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Santos et al. (2018)	Path analysis of phenotypic traits in young cacao plants under drought conditions	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Allard et al. (2016)	Detecting QTLs and putative candidate genes involved in budbreak and flowering time in an apple multiparental population	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Houel et al. (2015)	Identification of stable QTLs for vegetative and reproductive traits in the microvine (*Vitis vinifera* L.) using the 18 K Infinium chip	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Meggio et al. (2014)	Biochemical and physiological responses of two grapevine rootstock genotypes to drought and salt treatments	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Nicolas et al. (2016)	Genetic diversity, linkage disequilibrium and power of a large grapevine (*Vitis vinifera* L) diversity panel newly designed for association studies	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Romeu Santacreu et al. (2014)	Quantitative trait loci affecting reproductive phenology in peach	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Velasco et al. (2016)	Evolutionary genomics of peach and almond domestication	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Plant breeding
Torres et al. (2016)	Berry quality and antioxidant properties in *Vitis vinifera* cv. Tempranillo as affected by clonal variability, mycorrhizal inoculation and temperature	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Shift crop/cultivar

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Rippke et al. (2016)	Timescales of transformational climate change adaptation in sub-Saharan African agriculture	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Shift crop/cultivar
Adiga et al. (2019)	Phenological growth stages of the cashew tree (*Anacardium occidentale* L.) according to the extended BBCH scale	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Shift crop/cultivar
West (2019)	Multi-criteria evolutionary algorithm optimization for horticulture crop management	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Shift crop/cultivar
Schroth et al. (2017)	From site-level to regional adaptation planning for tropical commodities: cocoa in West Africa	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Shift planting area
Adhikari et al. (2015)	Climate change and eastern Africa: a review of impact on major crops	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Water management
Adamides et al. (2020)	Climate change and eastern Africa: a review of impact on major crops	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Water management
Trigo-Córdoba et al. (2015)	Effects of deficit irrigation on the performance of grapevine (*Vitis vinifera* L.) cv. 'Godello' and 'Treixadura' in Ribeiro, NW Spain	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Water management
Devine and Anthony Toby (2019)	Climate-smart management of soil water storage: statewide analysis of California perennial crops	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Water management
Galindo et al. (2018)	Deficit irrigation and emerging fruit crops as a strategy to save water in Mediterranean semiarid agrosystems	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Water management
Hayes et al. (2015)	Species-specific responses to ozone and drought in six deciduous trees	Tree fruits and nuts	Fig. 5.10 (Adaptation)			Water management
Potopová et al. (2017)	The impacts of key adverse weather events on the field-grown vegetable yield variability in the Czech Republic from 1961 to 2014	Vegetables	Fig. 5.3 (Observed)	Eastern Europe		
Brás et al. (2021)	Severity of drought and heatwave crop losses tripled over the last five decades in Europe	Vegetables	Fig. 5.3 (Observed)	Eastern Europe, Southern Europe, Western Europe		
Olivares (2018)	Tropical rainfall conditions in rainfed agriculture in Carabobo, Venezuela	Vegetables	Fig. 5.3 (Observed)	Latin America and the Caribbean		
Giorgini et al. (2019)	Current strategies and future outlook for managing the Neotropical tomato pest *Tuta absoluta* (Meyrick) in the Mediterranean Basin	Vegetables	Fig. 5.3 (Observed)	Northern Africa, Southern Europe		
Hu et al. (2019)	Five newly collected turnip mosaic virus (Tumv) isolates from Jeju Island, Korea are closely related to previously reported Korean Tumv isolates but show distinctive symptom development	Vegetables	Fig. 5.3 (Observed)	Southeastern Asia		
Kabir et al. (2017)	Farm-level adaptation to climate change in Western Bangladesh: an analysis of adaptation dynamics, profitability and risks	Vegetables	Fig. 5.3 (Observed)	Southern Asia		
Vaidya et al. (2018)	Land use and land cover changes in Kullu valley of Himachal Pradesh	Vegetables	Fig. 5.3 (Observed)	Southern Asia		
Adebisi-Adelani 2016)	Citrus and tomatoes response to climate change: survey of farmers' perception and adaptation strategies in northern Nigeria	Vegetables	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Chepkoech et al. (2018)	Farmers' perspectives: impact of climate change on African indigenous vegetable production in Kenya	Vegetables	Fig. 5.3 (Observed)	Sub-Saharan Africa		

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Phophi et al. (2020)	Perceptions of climate change and drivers of insect pest outbreaks in vegetable crops in Limpopo Province of South Africa	Vegetables	Fig. 5.3 (Observed)	Sub-Saharan Africa		
Georgopoulou et al. (2017)	Climate change impacts and adaptation options for the Greek agriculture in 2021–2050: a monetary assessment	Vegetables	Fig. 5.8 (Projection)		Climate change	
Giannini et al. (2017)	Projected climate change threatens pollinators and crop production in Brazil	Vegetables	Fig. 5.8 (Projection)		Ecosystem services	
Ramos et al. (2018)	Mapping global risk levels of *Bemisia tabaci* in areas of suitability for open field tomato cultivation under current and future climates	Vegetables	Fig. 5.8 (Projection)		Pests and Diseases	
Litskas et al. (2019)	Impacts of climate change on tomato, a notorious pest and its natural enemy: small scale agriculture at higher risk	Vegetables	Fig. 5.8 (Projection)		Pests and Diseases	
Cammarano et al. (2020)	Impact of climate change on water and nitrogen use efficiencies of processing tomato cultivated in Italy	Vegetables	Fig. 5.8 (Projection)		Phenology	
Van de Perre et al. (2015)	Climate impact on Alternaria moulds and their mycotoxins in fresh produce: the case of the tomato chain	Vegetables	Fig. 5.8 (Projection)		Temperature	
Giuliani et al. (2019)	Identifying the most promising agronomic adaptation strategies for the tomato growing systems in Southern Italy via simulation modeling	Vegetables	Fig. 5.8 (Projection), Fig 5.10 (Adaptation)		Temperature, Precipitation	Water management, Shift crop/cultivar, Shift planting date
Diacono et al. (2016)	Combined agro-ecological strategies for adaptation of organic horticultural systems to climate change in Mediterranean environment	Vegetables	Fig. 5.10 (Adaptation)			Agroecology
Asadu et al. (2018)	Climate change information source and indigenous adaptation strategies of cucumber farmers in Enugu State, Nigeria	Vegetables	Fig. 5.10 (Adaptation)			Agroecology, Agronomy, On-farm diversity, Shift crop/cultivar, Shift planting date, Water management
Cámara-Zapata et al. (2020)	Evaluation of an adapted greenhouse cooling system with pre-chamber and inflatable air ducts for semi-arid regions in warm conditions	Vegetables	Fig. 5.10 (Adaptation)			Agronomy
Liaqat et al. (2019)	Inducing effect of chitosan on the physiological and biochemical indices of eggplant (*Solanum melongena* L.) genotypes under heat and high irradiance	Vegetables	Fig. 5.10 (Adaptation)			Agronomy
Piñero et al. (2018)	Fruit quality of sweet pepper as affected by foliar Ca applications to mitigate the supply of saline water under a climate change scenario	Vegetables	Fig. 5.10 (Adaptation)			Agronomy
Adebisi-Adelani and Oyesola (2014)	Adaptation strategies of citrus and tomato farmers towards the effect of climate change in Nigeria	Vegetables	Fig. 5.10 (Adaptation)			Agronomy, Conservation agriculture, Shift crop/cultivar Shift area, Shift planting date
Tabbo and Amadou (2017)	Assessing newly introduced climate change adaptation strategy packages among rural households: evidence from Kaou local government area, Tahoua State, Niger Republic	Vegetables	Fig. 5.10 (Adaptation)			Agronomy, Conservation agriculture, Water management, Shift crop/cultivar
Sharma (2014)	Climate change effects on insects: implications for crop protection and food security	Vegetables	Fig. 5.10 (Adaptation)			Climate services

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Alliaume et al. (2014)	Reduced tillage and cover crops improve water capture and reduce erosion of fine textured soils in raised bed tomato systems	Vegetables	Fig. 5.10 (Adaptation)			Conservation agriculture
Li et al. (2019b)	Yields and resilience outcomes of organic, cover crop, and conventional practices in a Mediterranean climate	Vegetables	Fig. 5.10 (Adaptation)			Conservation agriculture
Mpanga et al. (2020)	Sustainable agriculture practices as a driver for increased harvested cropland among large-scale growers in Arizona: a paradox for small-scale growers	Vegetables	Fig. 5.10 (Adaptation)			Conservation agriculture
Markou et al. (2020)	Addressing climate change impacts on agriculture: adaptation measures for six crops in Cyprus	Vegetables	Fig. 5.10 (Adaptation)			Conservation agriculture, Shift crop/cultivar
Ebert (2014)	Potential of underutilized traditional vegetables and legume crops to contribute to food and nutritional security, income and more sustainable production systems	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Kaushik et al. (2016)	Phenotyping of eggplant wild relatives and interspecific hybrids with conventional and phenomics descriptors provides insight for their potential utilization in breeding	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Nankishore and Farrell (2016)	The response of contrasting tomato genotypes to combined heat and drought stress	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Xu et al. (2017)	Mapping quantitative trait loci for heat tolerance of reproductive traits in tomato (*Solanum lycopersicum*)	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Shaheen et al. (2016)	Morpho-physiological evaluation of tomato genotypes under high temperature stress conditions	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Driedonks et al. (2018)	Exploring the natural variation for reproductive thermotolerance in wild tomato species	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Conesa et al. (2020)	Mediterranean long shelf-life landraces: an untapped genetic resource for tomato improvement	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Seymen et al. (2019)	Identification of drought-tolerant pumpkin (*Cucurbita pepo* L.) genotypes associated with certain fruit characteristics, seed yield, and quality	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Fullana-Pericàs et al. (2019)	Tomato landraces as a source to minimize yield losses and improve fruit quality under water deficit conditions	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Song et al. (2020a)	Development and application of a PCR-based molecular marker for the identification of high temperature tolerant cabbage (*Brassica oleracea* var. *capitata*) genotypes	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Scarano et al. (2020)	Selection of tomato landraces with high fruit yield and nutritional quality under elevated temperatures	Vegetables	Fig. 5.10 (Adaptation)			Plant breeding
Houshmandfar et al. (2019)	Crop rotation options for dryland agriculture: an assessment of grain yield response in cool-season grain legumes and canola to variation in rainfall totals	Vegetables	Fig. 5.10 (Adaptation)			Shift crop/cultivar

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Abhayapala et al. (2018)	Exploitation of differential temperature-sensitivities of crops for improved resilience of tropical smallholder cropping systems to climate change: a case study with temperature responses of tomato and chilli	Vegetables	Fig. 5.10 (Adaptation)			Shift crop/cultivar
Nziku et al. (2016)	Climate change adaptation in vulnerable crop and livestock production systems in Mgeta, Tanzania	Vegetables	Fig. 5.10 (Adaptation)			Shift crop/cultivar, On-farm diversity
Kabir et al. (2018)	Bio-economic evaluation of cropping systems for saline coastal Bangladesh: I. Biophysical simulation in historical and future environments	Vegetables	Fig. 5.10 (Adaptation)			Shift planting date
Mubarak (2020)	Improving water productivity and yield onion crop by combining early planting and straw mulch under different irrigation levels in dry mediterranean region	Vegetables	Fig. 5.10 (Adaptation)			Shift planting date, Water management
Rodriguez-Ortega et al. (2017)	Use of a smart irrigation system to study the effects of irrigation management on the agronomic and physiological responses of tomato plants grown under different temperatures regimes	Vegetables	Fig. 5.10 (Adaptation)			Water management
Giuliani et al. (2017)	Deficit irrigation and partial root-zone drying techniques in processing tomato cultivated under Mediterranean climate conditions	Vegetables	Fig. 5.10 (Adaptation)			Water management
Van Dijl et al. (2015)	Determinants of adoption of drought adaptations among vegetable growers in Florida	Vegetables	Fig. 5.10 (Adaptation)			Water management
Monteiro et al. (2020)	Current status and trends in Cabo Verde agriculture	Vegetables	Fig. 5.10 (Adaptation)			Water management
Bird et al. (2016)	Modelling climate change impacts on and adaptation strategies for agriculture in Sardinia and Tunisia using AquaCrop and value-at-risk	Vegetables	Fig. 5.10 (Adaptation)			Water management
Valcárcel et al. (2020)	Controlled deficit irrigation as a water-saving strategy for processing tomato	Vegetables	Fig. 5.10 (Adaptation)			Water management
Mohammed et al. (2018)	Deficit irrigation for improving the postharvest quality of lowland tomato fruits	Vegetables	Fig. 5.10 (Adaptation)			Water management
Yu et al. (2020)	Global synthesis of the impact of droughts on crops' water-use efficiency (WUE): towards both high WUE and productivity	Vegetables	Fig. 5.10 (Adaptation)			Water management
Brainard et al. (2019)	Managing drought risk in a changing climate: irrigation and cultivar impacts on Michigan asparagus	Vegetables	Fig. 5.10 (Adaptation)			Water management
Jokisch et al. (2016)	Small scale rain- and floodwater harvesting for horticulture in central-northern Namibia for livelihood improvement and as an adaptation strategy to climate change	Vegetables	Fig. 5.10 (Adaptation)			Water management
Ronchetti et al. (2020)	Crop row detection through UAV surveys to optimize on-farm irrigation management	Vegetables	Fig. 5.10 (Adaptation)			Water management
Choquette et al. (2016)	The organizational dimensions of agricultural adaptation: experiences in Québec's market garden sector	Vegetables	Fig. 5.10 (Adaptation)			Water management
Declaro-Ruedas (2020)	Strategies use by garlic growers in coping with climate variability in Occidental Mindoro, Philippines	Vegetables	Fig. 5.10 (Adaptation)			Water management

Citation	Title	Crop type	Figure	Region (Figure 5.3)	Driver (Figure 5.8)	Adaptation (Figure 5.10)
Bafdal et al. (2018)	Water harvesting as a technological innovation and greater solving of climatic change impact to supply fertigation	Vegetables	Fig. 5.10 (Adaptation)			Water management
Emami and Koch (2018)	Agricultural water productivity-based hydro-economic modeling for optimal crop pattern and water resources planning in the Zarrine River Basin, Iran, in the wake of climate change	Vegetables	Fig. 5.10 (Adaptation)			Water management
Georgopoulou et al. (2017)	Climate change impacts and adaptation options for the Greek agriculture in 2021–2050: a monetary assessment	Vegetables	Fig. 5.10 (Adaptation)			Water management, Shift crop/cultivar Shift planting date
Shivamurthy et al. (2015)	Impact of climate change and adaptation measures initiated by farmers	Vegetables	Fig. 5.10 (Adaptation)			Water management, Shift crop/cultivar Shift planting date

SM5.3 Projected Impacts on Growing Area Suitability

AR5 provided medium evidence that warmer temperatures had benefited agriculture in the northern latitudes (Porter et al., 2014). Since then, additional evidence shows that further warming is expected to increase climate suitability in some temperate regions for crops such as grapes (Section 5.4.3; Zabel et al., 2014; Nemoto et al., 2016; Machar et al., 2017; Irimia et al., 2018), subtropical citrus (tankan) (Sugiura et al., 2014), banana and macadamia nuts in high altitudes in Nepal (Table SM5.3; Ranjitkar et al., 2016b). Caution must be taken about these projected increases in growing area suitability, given the need of changing land and other limitations (Table SM5.3). (Manners and van Etten, 2018) generated global crop suitability projections for grain legumes, root crops and cereals, and found that suitable growing areas of tropical root crops, such as cassava and sweet potato, would increase due to warming. In contrast, another global study assessing climatic suitability of 27 major food crops and seven livestock species projected that 10% of the current food production areas will become unsuitable in mid-century (2041–2060) and 31–34% in end-century (2081–2100) under SSP5-8.5 (Kummu et al., 2021), with severe implications for the current growing regions. Regionally, most of the tropical and subtropical regions along with semi-arid areas are expected to show a decline or a shift in suitability due to both warming and drying trends for olives (Alfieri et al., 2019); for coffee (Bunn et al., 2015; Ovalle-Rivera et al., 2015; Imbach et al., 2017; Moat et al., 2017; Fain et al., 2018; DaMatta et al., 2019); for grapes in China (Jiang et al., 2015); for passion fruit (Bezerra et al., 2019); for cotton grown in Australia (Shabani and Kotey, 2016); and for wine (see Box 5.2).

Table SM5.3 | Projected impacts of climate change on growing area suitability.

Crop commodity	Sub regions/ countries	Emission scenario/ time period	Climate index	Projected change	Reference
Maize	West Africa/ Sudan	RCP2.6, 8.5/ 2080	Average temperature, average precipitation	Suitability conditions will change in at least 43% of the region. In dry lowlands, larger rainfall will increase suitability in the Sudano-Sahelian savannas. Suitability of rainfed maize production in the wet lowlands will see no change by mid-century, but it will decrease toward the end of the century under RCP8.5 owing to rising temperatures. In the wet mid-latitudes, suitability is projected to increase with generally adequate rainfall and temperature ranges.	Ugbaje et al. (2019)
Maize	East Asia/China	1.5°C and +2.0°C	Annual average temperature	The summer maize cultivation climatically suitable region (CSR) shifts eastwards. The optimum areas for maize will shift north-eastward under RCP4.5 and RCP8.5. The optimum area will decrease by 38% under RCP4.5 and 46% under RCP8.5 when temperature rises from +1.5°C to +2.0°C.	He et al. (2019)
Maize, soybean, wheat, cotton, grassland and forest	North America/ USA (16 states)	RCP2.6, 4.5 and 8.5 /2040, 2070, 2100	Air temperature, precipitation	RCP2.6: Almost no change in suitable areas in maize, soybean and winter wheat. Spring wheat will lose almost half its suitable areas in mid- to late-century. RCP4.5: Maize and soybean will lose suitable areas from 2070 onward. Suitable area for spring wheat is projected to decrease greatly from 2040 onward. Soybean will lose suitable areas from 2070 onward. RCP8.5: Spring wheat will lose almost half its suitable areas in mid- to late-century. Soybean will lose suitable areas from 2070 onward with a much greater extent than RCP4.5.	Lant et al. (2016); Singh et al. (2017)

Crop commodity	Sub regions/ countries	Emission scenario/ time period	Climate index	Projected change	Reference
Maize and rice	East Asia/China	RCP2.6and 8.5/2021–2100	Climatic and hydrological factors	Under RCP2.6, suitable areas for both crops will show little change over time. Under RCP8.5, suitable areas will shift northward and expand from northwestern to northern China, as a result of greater warming in northern China and the faster warming trend.	Zhang et al. (2017)
Winter wheat	East Europe/ Russia	RCP4.5 and 8.5/1950–2099	Thermal suitability	In all scenarios, projected thermal suitability shifts toward the northwestern and the Far East regions. Increases of extreme heat in the southern regions (currently the most productive and intensively managed area).	Di Paola et al. (2018)
Wheat and cotton	Australasia/ Australia	SRES A2 (CSIRO-Mk3.0, MIROC-H)/2030, 2050, 2070, 2100	CLIMEX version 3.02 based on thermo-hydrological growth index and cold, heat, dry and wet stresses	Suitable areas for wheat and cotton will decrease from 2030 to 2070. Only a few southern regions of Australia will be suitable for wheat in 2030–2100. Cotton can be grown in many areas until 2070, but suitable areas will decrease toward 2100, mainly due to desiccation.	Shabani and Kotey (2016)
Cereals, legumes, root crops	Global	RCP4.5/2040	Temperature, precipitation	Suitable growing areas of tropical root crops, such as cassava and sweet potato, would increase due to warming.	Manners and van Etten (2018)
Cereals, legumes, root crops	Jamaica	+ 1.5°C and +2°C warming	Temperature, precipitation	Warming of less than 1.5°C will have an overall negative impact on crop suitability and a general reduction in the range of crops. Above the +1.5°C threshold, even more irreversible changes to the sustainability of Jamaica's agriculture sector are projected.	Rhiney et al. (2018)
14 major crops in California	North America/ USA	RCP8.5/2040–2069	Minimum and maximum temperature	Currently high-producing counties will have the largest absolute impact by increasing temperatures. The relative impact will be greater in Northern Sacramento Valley counties where heat-sensitive perennial crops are dominant.	Kerr et al. (2018)
Open field tomato	Global	RCP2.6, 4.5, 6.0, 8.5/2050–2070	Temperature, precipitation	Tomato will lose its suitable areas in all continents except for some countries in Europe. RCP6.0 and RCP8.5 show a larger decrease in suitable areas than RCP2.6 and 4.5. The decrease is particularly large in Africa, South America, Australia and China.	Ramos et al. (2019)
Open field tomato	Global	RCP4.5/2050–2070	Temperature, precipitation	In 2050, an expansion of 180% in areas under high risk of *B. tabaci*. In 2070, an extension of 164% in areas under high risk.	Ramos et al. (2018)
Citrus Tankan Hayata	East Asia/Japan	SRES-A1B (MIROC3.2)/2060	Air temperature	An expansion of suitable area for subtropical Tanakan Hataya to central Japan by 2050. Tankan could be produced as a substitute in coastal areas of the current satsuma mandarin-producing regions.	Sugiura et al. (2014)
Apples, pears, plums and others	West Europe/ UK	SRES A1B/2050	Relative index of pollinator availability	In the 2050s, the most suitable areas for orchards will become low in pollinator availability. Pollinator availability may persist in areas currently used for fruit production.	Polce et al. (2014)
Grape	Global	RCP2.6, RCP6.0/2099	Mean and minimum temperature precipitation, evaporation	Differences between climate models were greater than those between RCPs. Overall, there will be a lack of water to maintain current levels of production in all regions. Thermal suitability will be greatly affected in China and the Mediterranean region. The possibility of quality wines is not altered.	Santillan et al. (2019)
Grape	South Europe/ Italy	RCP4.5, RCP8.5/2006–2100	Air temperature, crop water stress index	(1) Within 2010–2040, 41% of the area suitable for cultivar Aglianico cultivation will need irrigation. (2) By 2100, climate change benefits for the cultivation of Aglianico will decrease, as well as the suitable areas. Suitable area for cultivation in 2100 will decrease to 24% under RCP4.5 and 5% under RCP8.5.	Bonfante et al. (2018)
Grape	Europe	RCP8.5/2046–2070	Temperature, evapotranspiration	In southern Europe, increases in the cumulative thermal stress and dryness are projected to decrease production and quality, and to increase water requirements. In western and central Europe, high-quality areas for viticulture will significantly extend northward.	Cardell et al. (2019)
Grape	South Europe/ Italy (Emilia-Romagna region)	RCP4.5, RCP8.5/2011–2040, 2071–2100	Minimum and maximum temperature, precipitation	Most of the region will remain suitable for grape production during the period 2011–2040 under both RCPs. During the period 2071–2100, the entire region will become too hot for production under the RCP 8.5, whereas under the RCP 4.5, changes will be milder, suggesting that the Emilia-Romagna region could still be suitable for grape cultivation but would require certain adjustments.	Teslić et al. (2019)
Coffee	Latin America and the Caribbean/ Nicaragua	SRES-A2/2040–2069	Temperature, precipitation	By 2050, the suitability of areas to grow arabica coffee in Nicaragua will move approximately 300 m up the altitudinal gradient. Farmers at lower elevations will no longer be able to grow quality coffee and may have to abandon it.	Läderach et al. (2017)

Crop commodity	Sub regions/ countries	Emission scenario/ time period	Climate index	Projected change	Reference
Walnut	West Asia/ Iran	RCP4.5/2020–2049	Temperature, precipitation	Current suitable area will be reduced by ~6%, from 582,844 km^2 to 546,710 km^2 by mid-century.	Vahdati et al. (2019)
Almonds, pistachios	North Africa/ Tunisia	RCP4.5,8.5/2041–2070, 2071–2100	Chilling requirements	Chilling requirements for both species will be hard to meet in time under all climate scenarios. There will be a yield penalty as a result of delayed timing of development. Viability of temperate nut production will be reduced.	Benmoussa et al. (2017)
Cocoa	West Africa / Cameroon, Côte d'Ivoire, Ghana, Liberia, Niger, Nigeria, Sierra Leone	RCP6.0/2050s	Maximum temperature, precipitation, number of consecutive months with <100 mm precipitation, evapotranspiration	Maximum temperatures during the dry season will become more limiting to cocoa growth suitability by mid-century. The most negative effects are projected in Togo, Nigeria, Guinea and northeastern Côte d'Ivoire. Cameroon, Ghana, southern Côte d'Ivoire and Liberia will generally be less affected, with locally positive effects.	Schroth et al. (2016)
Eight major tree crops	Southern Europe/ Portugal	RCP4.5, 8.5/2041–2070	Growing degree hours, chilling portions	Under both RCPs, periods of very high temperatures will make many locations unsuitable for the trees that are currently cultivated. The size of the effects will be stronger under RCP8.5.	Santos et al. (2017)

SM5.4 Change in the Number of Days per Year above 'Extreme Stress' Values from 2000 to the 2090s

SM5.4.1 Methodology

Figures 5.12 and 5.18 both use the concept of an index derived from climate variables that measures the effects of climate change on heat stress in humans and domesticated livestock. The index formulae have been developed by experts and published in the peer-reviewed literature (references below). The climate data are from the CMIP6 ensemble of results. The ISIMIP project (https://www.isimip.org) selected data from five Earth system models, and did bias correction and downscaling as needed to produce a combined data set of baseline and future conditions at 0.5° latitude–longitude resolution for the Earth's surface for 11 commonly used climate variables. For this analysis, we used the following:

Table SM5.4 | Climate variables used to calculate the heat stress index.

Variable description	Short name(s)	Original units
Near-surface relative humidity	hurs	%
Near-surface air temperature:		
Maximum daily temperature	tmax/tasmax	K
Average daily temperature	tave/tas	K

In post-processing, temperature variables were converted to degrees Celsius. A land-only/non-Antarctica mask was used to limit data to relevant areas for these two figures.

The data from ISIMIP come as single Earth system model, single variable, daily data sets for two scenarios for 10 years: SSP1-2.6 and SSP5-8.5. These two scenarios bound the range of plausible, if low probability, on the low and hide side. The analysis combines these 10-year data sets into single-model 20-year sets for three periods: 1991–2010 (early century), 2041–2060 (mid-century) and 2081–2100 (end-century).

For each variable, a model-specific, time-period representative daily data set was created by averaging across all 20 years for each day. The result is a spatial data set that for each 0.5° grid cell has 366 observations for each model. The leap day values were averaged over just the number of leap days in the 20-year period.

These data were then used to estimate extreme stress in five domesticated livestock species (cattle, sheep, goats, poultry and pigs) as outlined in Thornton et al. (2021).

For humans (Foster et al., 2021), we used:

Equation SM5.1:

$$PWC = \frac{100}{1 + \left(\left(\frac{-12.28 \cdot \log(hurs) + 87.99}{tas} \right)^{-2.21 \cdot \log(hurs) + 2.63} \right)}$$

This measurement is of physical work capacity (PWC) relative to a non-stressful environment. The cut-off value for humans is a 40% reduction in work capacity over a 1-h period. This understates the impact of climate change because, as work continues during the day, capacity to work declines. The number in Figure 5.18 is the count of days per year where the index value is less than 60; that is, a loss of 60% of work capacity.

SM5.5 Supplementary Materials Used for Assessments of Regional Fisheries Management Organization Climate Awareness for Figure MOVING PLATE.3 in Chapter 5

FAO (2017) Bay of Bengal Programme (2013) FAO (2019c) Russian Federation (2019) FAO (2019a) IPHC (International Pacific Halibut Commission) Secretariat (2020) FAO (2020c) Pacific Islands Forum Fisheries Agency (2018–19) Fisheries Committee for the West Central Gulf of Guinea (FCWC) (2018) Regional Commision of Fisheries of Gulf of Guinea (2019) Northwest Atlantic Fisheries Organization (2019) North Atlantic Salmon Conservation Organization (2019) North-East Atlantic Fisheries Commission (2019) North Pacific Fisheries Commission (NPFC) (2020) Pacific Community (2019)	FAO (2017) South East Atlantic Fishereis Organization (2019) Southern Indian Ocean Fisheries Agreement (SIOFA) (2019) South Pacific Regional Fisheries Management Organization (2020) FAO (2019b) The Commission for the Conservation and Management of Highly Migratory Fish Stocks in the Western and Central Pacific Ocean (2019) FAO (2020d) Miniterial Conference on Fisheries Cooperation among African States Bordering the Atlantic Ocean (COMHAFAT) (2019) Indian Ocean Tuna Commission (IOTO) (2019) North-East Atlantic Fisheries Commision (2019) International Commission for the conservation of Atlantic Tunas (2019) Inter-American-Tropical-Tuna-Commission (IATTC) (2018)

SM5.6 Supplementary Materials for Ocean-based and Inland Aquaculture Systems

SM5.6.1 Assessment Questions Used to Clarify and Enable Consistency in Expert Assessments for Inland and Brackish Aquaculture (Salinities of <10 ppm and/or No Connection to the Marine Environment) Sectors

Assessments were made for species accounting for 95% of inland, brackish and marine aquaculture production by weight from 2018 FAO FishstatJ data (FAO, 2020b).

Table SM5.5 | Assessment questions used to clarify and enable consistency in expert assessments for inland and brackish aquaculture vulnerability assessments.

Quantifier	What question does this seek to address?
Food security at local level	Is the region reliant on aquaculture for consumption (personal or small scale)?
Livelihood	Is the region mostly reliant on aquaculture for income and/or employment?
Land use conflict	Does the region experience conflict over land usage and aquaculture, i.e., mangrove deforestation, inland aquaculture, dams?
Water use conflict	Does the region experience conflict over water usage and aquaculture, i.e., is there limited freshwater?
Social inequity	Are aquaculture sectors more likely to generate inequity under climate change than other food production systems?

Table SM5.6 | Assessment questions used to clarify and enable consistency in expert assessments for inland and brackish aquaculture mitigation assessments.

Quantifier	What question does this seek to address?
Alternative energies	Are alternative energies likely to be available and used to reduce GHG emissions?
Source of feeds	Are alternative feeds being used that reduce GHG emissions and pressure on other production systems (e.g., certified soy (not coming from forest land conversion), by-products from fisheries or aquaculture or other uses)?
Feed conversion efficiency	Are there technological and genetic improvements in place that increase feed conversion efficiency (thereby reducing waste and GHG emissions)?
Governance[a]	Does the local or national governance have the capacity, willingness and ability to enforce strategies to reduce GHG emissions for the aquaculture sector?
Low GHGE species	Does the species being cultured require less GHGE input than other culture species?

Table notes:

(a) For governance, the mitigation response options were: Low, low mitigation potential, that is, governance is unlikely to develop or make GHG reduction strategies mandatory; Medium, medium mitigation potential, that is, there is some indication that governance would promote GHG reduction strategies; High, high mitigation potential, that is, governance strongly promotes reduction of GHG emissions.

Table SM5.7 | Assessment questions used to clarify and enable consistency in expert assessments for inland and brackish aquaculture projected impact assessments.

Quantifier	What question does this seek to address?
Global warming	Will predicted climate changes in ecosystem temperatures affect aquaculture productivity?
Deoxygenation	Will predicted climate changes reduce oxygen levels (including via temperature associated deoxygenation) and affect productivity?
Freshwater availability	Will predicted climate changes to freshwater availability and delivery patterns affect productivity?
Precipitation changes (including droughts)	Will predicted climate changes in precipitation and droughts affect productivity?
Eutrophication	Will predicted climate change increase eutrophication, therefore affecting productivity?
Harmful algal blooms	Will predicted climate changes increase impacts of HABs on productivity and marketing?
Food safety	Will climate change increase the incidence of parasites, pests and toxins in aquaculture products such that they become harmful to humans for food consumption?
Sea level rise	Will predicted climate changes in sea levels (coastal inundation) affect productivity and assets (aquaculture infrastructure, site access, etc.)?
Floods	Will predicted climate change associated floods increase negative impacts on productivity, human lives and assets (e.g., heavy rain, snow melt)?
Cyclones/hurricanes/ severe storms/ extreme events	Will predicted climate change increases in cyclones, hurricanes, severe storms or extreme events affect productivity via production system, assets, human lives and ecosystem damage?
Pathogens, parasites and pests	Will predicted climate changes affect pathogen, parasites and pests incidence or intensity, or will new disease threats emerge?
Juvenile availability	Will predicted climate changes affect the availability of wild-caught juveniles for aquaculture operations?
Aquaculture feed	Will predicted climate changes affect either fishmeal or plant-based derivatives for aquaculture feed?

Table SM5.8 | Assessment questions used to clarify and enable consistency in expert assessments for inland and brackish aquaculture adaptation and maladaptation assessments.

Quantifier	What question does this seek to address?
Combined food production	Is aquaponics or integrated aquaculture with other aquatic species or plants being used to reduce energy, water consumption or waste (environmental footprint)?
Biotechnology	Is selective breeding (e.g., genetic selection) being developed to improve climate resiliency?
Tolerant species/ strain selections	Are species or strains naturally tolerant to future climate conditions being cultured as an adaptation option?
Gender equity	Can aquaculture provide opportunities for addressing gender inequity and supporting food security for these groups under climate change?
Governance, national	Is national governance likely to support necessary changes for aquaculture, e.g., is aquaculture included in national adaptation plans or has a national strategy been developed? Can uncertainty be managed?
Governance, local	Is local governance able to support necessary changes for aquaculture related to climate change? Does it have capacity?
Insurance and financial support	Is there access to insurance and financial support in case of climate-related damage or claims?
Early warning systems	Are early-warning systems or networks in place to promote preparedness, prevention and adaptation to climate change?
Aquaculture feeds	Adaptation: Are alternative feeds or feed composition being considered that would likely increase adaptation, e.g., through reduced pressure between food production systems and use of by-products? Maladaptation: Are alternative feeds or feed composition being considered that would likely reduce maladaptation, e.g., through reduced pressure between food production systems and use of by-products?
Spatial planning	Is risk-based spatial planning being used to identify locations less susceptible to climate change threat?
Optimising fisheries–aquaculture interactions	Is aquaculture being developed or considered as a successful adaptation option for fisheries under threat of climate change? Consideration of trade-offs?
Best practice implementation	Are industry guidelines and practices promoting better management practices as a first step to adaptation and resiliency, e.g., FAO Responsible Fisheries, Ecosystem Approach to Aquaculture?
On-farm adaptation approaches	Are autonomous climate adaptation strategies being developed and applied at a farm level, e.g., reinstating coastal defenses (including biogenic habitat) to prevent pond inundation, use aeration systems to prevent oxygen depletion or eutrophication caused by thermal increases?

SM5.6.2 Assessment Questions Used to Clarify and Enable Consistency in Expert Assessments for Marine Aquaculture Sectors

Assessments were made for species accounting for 95% of inland, brackish and marine aquaculture production by weight from 2018 FAO FishstatJ data (FAO, 2020b).

Table SM5.9 | Assessment questions used to clarify and enable consistency in expert assessments for marine aquaculture vulnerability assessments.

Quantifier	What question does this seek to address?
Food security at local level	Is the region reliant on aquaculture for consumption (personal or small scale)?
Livelihood	Is the region reliant on aquaculture for income and/or employment?
Coastal and marine use conflict	Does the region experience conflict over space usage and aquaculture, i.e., mangrove deforestation, saltmarsh land change, Indigenous territories, fishery areas, land-based marine aquaculture?
Social inequity	Are aquaculture sectors more likely to generate inequity under climate change than other food production systems?

Table SM5.10 | Assessment questions used to clarify and enable consistency in expert assessments for marine aquaculture mitigation assessments.

Quantifer	What question does this seek to address?
Alternative energies	Are alternative energies likely to be available and used to reduce GHG emissions?
Source of feeds	Are alternative feeds being developed that reduce GHG emissions and pressure on other production systems (e.g., certified soy, by-products from fisheries or aquaculture or other uses)?
Feed conversion efficiency	Are there technological and genetic improvements in place that increase feed conversion efficiency (thereby reducing waste and GHG emissions)?
Governance*	Does the local or national governance have the capacity, willingness and ability to enforce strategies to reduce GHG emissions for the aquaculture sector?
Low-GHGE species	Does the species being cultured require less GHGE input than other culture species?

Table notes:

* For governance, the mitigation response options were: Low, low mitigation potential, that is, governance is unlikely to develop or make GHG reduction strategies mandatory; Medium, medium mitigation potential, that is, there is some indication that governance would promote GHG reduction strategies; High, high mitigation potential, that is, governance strongly promotes reduction of GHG emissions.

Table SM5.11 | Assessment questions used to clarify and enable consistency in expert assessments for marine aquaculture projected impact assessments.

Quantifer	What question does this seek to address?
Global warming	Will predicted climate changes in ecosystem temperatures affect productivity?
Deoxygenation	Will predicted climate changes reduce oxygen levels (including via temperature and or salinity associated deoxygenation) and affect productivity?
Precipitation changes (including droughts and freshwater discharge)	Will predicted climate changes in freshwater patterns and inputs to coastal ecosystems affect productivity (including droughts, coastal flooding and freshwater discharge)?
Acidification	Will predicted changes in ecosystem carbonate levels affect productivity?
Eutrophication	Will predicted climate change increase eutrophication, therefore affecting productivity?
Harmful algal blooms	Will predicted climate changes increase negative impacts of HABs on productivity and marketing?
Food safety	Will climate change increase the incidence of parasites, pests and toxins in aquaculture products such that they become harmful to humans for food consumption?
Sea level rise	Will predicted climate changes in sea levels (coastal inundation) affect productivity and assets (aquaculture infrastructure, site access, etc.)?
Extreme wave heights	Will predicted climate change affect the incidence and size of waves that may affect productivity, human lives and assets?
Cyclones/hurricanes/ severe storms/extreme events	Will predicted climate change increases in cyclones, hurricanes, severe storms or extreme events affect productivity via production system, human lives, assets and ecosystem damage?
Circulation patterns and strength	Will changes in currents and upwelling affect productivity and species?
Pathogens, parasites and pests	Will predicted climate changes affect pathogen and parasite incidence or intensity, or will new disease threats emerge, including increase in pests such as jellyfish blooms?
Juvenile availability	Will predicted climate changes affect the availability of wild-caught juveniles for aquaculture operations?
Aquaculture feed	Will predicted climate changes affect either fishmeal or plant-based derivatives for aquaculture feed?
Primary productivity	Will predicted climate change affect coastal and ocean primary productivity?

Table SM5.12 | Assessment questions used to clarify and enable consistency in expert assessments for marine aquaculture adaptation and maladaptation assessments.

Quantifer	What question does this seek to address?
Combined food production	Is aquaponics or integrated aquaculture with other aquatic species or plants being used to reduce energy, water consumption or waste (environmental footprint)?
Biotechnology	Is selective breeding (e.g., genetic selection) being developed to improve climate resiliency?
Tolerant species/ strain selections	Are species or strains naturally tolerant to future climate conditions being cultured as an adaptation option?
Gender equity	Can aquaculture provide opportunities for addressing gender inequity and supporting food security for these groups under climate change?
Governance, national	Is national governance likely to support necessary changes for aquaculture, e.g., is aquaculture included in national adaptation plans or has a national strategy been developed? Can uncertainty be managed?
Governance, local	Is local governance able to support necessary changes for aquaculture related to climate change? Does it have capacity?
Insurance and financial support	Is there access to insurance and financial support in case of climate-related damage or claims?
Early warning systems	Are early-warning systems or networks in place to promote preparedness, prevention and adaptation to climate change?
Aquaculture feeds	Adaptation: Are alternative feeds or feed composition being considered that would likely increase adaptation, e.g., through reduced pressure between food production systems and use of by-products? Maladaptation: Are alternative feeds or feed composition being considered that would likely reduce maladaptation, e.g., through reduced pressure between food production systems and use of by-products?
Spatial planning	Is risk-based spatial planning being used to identify locations less susceptible to climate change threat?
Optimising fisheries–aquaculture interactions	Is aquaculture being developed or considered as a successful adaptation option for fisheries under threat of climate change? Consideration of trade-offs?
Best practice implementation	Are industry guidelines and practices promoting better management as a first step to adaptation and resiliency, e.g., FAO Responsible Fisheries, Ecosystem Approach to Aquaculture?
On-farm adaptation approaches	Are autonomous climate adaptation strategies being developed and applied at a farm level, e.g., reinstating coastal defenses (including biogenic habitat) to prevent pond inundation, use aeration systems to prevent oxygen depletion or eutrophication caused by thermal increases?

SM5.6.3 Additional Bibliography Used for Assessments in Figures 5.14, 5.15 and 5.16

In addition to references used in the Chapter 5 text, the following literature was used for Figures 5.14, 5.15 and 5.16 in answering questions from Tables SM5.5–SM5.12:

Abass et al. (2020)
Adams et al. (2019)
Akinsorotan et al. (2019)
Alleway et al. (2019)
Ansah et al. (2014)
Aragão et al. (2020)
Arechavala-Lopez et al. (2020)
Atindana et al. (2019)
Ayisi et al. (2017)
Bartley et al. (2018)
Bergsson et al. (2019)
Besson et al. (2016)
Bissattini et al. (2015)
Brisbin and Mitarai (2019)
Buentello et al. (2000)
Carreira et al. (2017)
Casas-Prat and Wang (2020)
Catalán et al. (2019)
Chaitanawisuti et al. (2013)
Chan et al. (2018)
Chapra et al. (2017)
Chávez et al. (2019)
Chen et al. (2018)
Chilakala et al. (2019)
Christiansen (2019)
Clough et al. (2020)
Colombo et al. (2019)
Cominassi et al. (2019)
Cowx (2005)
Crichigno and Cussac (2019)
Crozier et al. (2019)
Cuellar-Martinez et al. (2019)
Cummings et al. (2019)
Dalvi et al. (2009)
DeWitte-Orr et al. (2019)
Dörr et al. (2020)
El-Sayed (2017)
El Hourany et al. (2021)
Engelbrecht et al. (2015)
Fang et al. (2019)
FAO (2011)
FAO (2020a)
FAO (2020b)
Farmery et al. (2021)
Fellous and Shama (2019)
Ficke (2005)
Fitzer et al. (2019b)
Fitzer et al. (2019a)
Forchino et al. (2017)
Gasco et al. (2018)
Gjedrem and Rye (2018)
Gobler (2020)
Gopalakrishnan et al. (2019)
Grasso et al. (2019)
Griffith and Gobler (2020)
Guillen et al. (2018)
Hanke et al. (2019)
Harvey (2017)
Hauer et al. (2016)
Hehre and Meeuwig (2016)
Hennon and Dyhrman (2020)
Ho and Goethals (2019)
Hoerterer et al. (2020)
Hossain et al. (2018)
Hu et al. (2012)
Huang et al. (2019)
Jansen et al. (2019)
Janssen et al. (2017)
Kais and Islam (2019)
Klinger et al. (2017)
Kongkeo (2005)
Lassalle and Rochard (2009)
Lee et al. (2019)
Lewis et al. (2020)
Li et al. (2019a)
Lind et al. (2019)
Liu et al. (2019a)
Liu et al. (2020)
Lobeto et al. (2021)
Loureiro et al. (2015)
Lu et al. (2019)
Lubchenco and Gaines (2019)
Müller et al. (2019)
Magnoni et al. (2019)
Martin et al. (2019)
Master et al. (2019)
Matthews and Berg (1997)
McClain and Romaire (2007)
Mearns et al. (2019)
Meucci et al. (2020)
Missaghi et al. (2017)
Mitz and Giesy (1985)
Mizuta and Wikfors (2019)
Moe et al. (2019)
Montalto et al. (2020)
Morim et al. (2021)
Nagy et al. (2020)
Naylor et al. (2021)
Niang et al. (2014)
Nkuba et al. (2019)
Olsvik et al. (2019)
Olusanya and van Zyll de Jong (2018)
Osinowo et al. (2018)
Paerl et al. (2018)
Pagès et al. (2020)
Paprocki (2018)
Patra et al. (2020)
Pauly (2019)
Peng et al. (2019)
Petrea et al. (2016)
Peyre et al. (2020)
Racault et al. (2017)
Ray et al. (2019b)
Rezk et al. (2009)
Riera-Heredia et al. (2020)
Roberts et al. (2019)
Rosa et al. (2012)
Roy-Basu et al. (2020)
Rubio et al. (2019)
Ruiz-Salmón et al. (2020)
Sae-Lim et al. (2017)
Salgado-Hernanz et al. (2019)
Sapiains A et al. (2019)
Sartini et al. (2017)
Satia (2017)
Schubel and Thompson (2019)
Soto et al. (2018)
Soto et al. (2019)
Soto et al. (2021)
Steinacher et al. (2010)
Stewart et al. (2019)
Stewart and Allen (2014)
Sun et al. (2015)
Sunny et al. (2019)
Tangka and Yusifu (2020)
Thompson et al. (2019)
Tiller et al. (2019)
Tittensor et al. (2019)
Tran-Ngoc et al. (2018)
Trono (2009)
Tuan et al. (2019)
Turner et al. (2019)
Uthe et al. (2018)
Wang et al. (2019a)
Wells et al. (2020)
Young and Ribal (2019)
Yue et al. (2019)
Zhang and Thomsen (2019)

SM5.7 Methodology and Materials Used for Adaptation Feasibility and Effectiveness Assessment and Limitations

SM5.7.1 Feasibility and Effectiveness Indicators

We followed approaches taken by Singh et al. (2020a) and Williams et al. (2021) for feasibility and effectiveness assessment of adaptation options that are currently implemented in production, distribution and consumption of food, fibre and other ecosystem products. We carefully examined their guiding questions for 19 indicators and selected 13 that characterised the feasibility of adaptation options (Table SM5.13). These are used in the current assessment with some modifications to the guiding questions (see Status in Table SM5.13). From the 19 indicators, we also selected guiding questions that are more closely associated with the effectiveness of adaptation options, which can be grouped into five effectiveness indicators defined by Owen (2020) (Table SM5.14).

Table SM5.13 | Selected feasibility indicators from Singh et al. (2020a) and its status compared with the original guiding questions.

Dimension	Feasibility indicators	Guiding questions	Status
Economic	Microeconomic viability	Does the option increase profitability for/raise income of adopters by increasing productivity or reducing the effective costs of inputs?	Modified
	Macroeconomic viability	Does the option contribute to greater GDP or reduced inflation?	Modified
Technological	Technical resource availability	Are the technology and associated human, financial, administrative resources needed for an adaptation option available?	Existing
Institutional	Political acceptability	Is the option politically acceptable?	Existing
	Legal, regulatory feasibility	Is it challenging to implement the legal chnages needed for the option? Are there known legal and regulatory barriers?	Existing
	Institutional capacity and administrative feasibility	Would current institutions be able to implement the option? Is the option administratively supported?	Existing
	Transparency and accountability potential	Would the option lead to transparency challenges? Is it difficult to account for the changes and for responsible implementation?	Modified
	Socio-cultural acceptability	Is there public resistance to the option? Does the option typically find acceptance within existing socio-cultural norms and sense of place and identity?	Existing
	Social and regional inclusiveness	Are different social groups and remote regions included in the option?	Existing
	Intergenerational equity	Does the option compromise the ability of future generations to meet their own needs in any way?	Existing
Environmental	Ecological capacity	Does the option enhance supporting, regulating or provisioning ecosystem services in any way?	Existing
	Adaptive capacity/resilience building potential	Does the option enhance the ability of systems, institutions and humans to adjust to potential damage, take advantage of opportunities, or respond to consequences? OR Does the option contribute to resilience building (ability to cope with stressors and reorganise to maintain structures and functions, retain capacity to transform)?	Existing
Geophysical	Physical feasibility	Is the physical potential for the adaptation option a constraint?	Existing

Table SM5.14 | Selected guiding questions from Singh et al. (2020a) , regrouped into five effectiveness indicators proposed by Owen (2020), with an additional question about maladaptation.

Effectiveness indicators	Guiding questions
(a) Reduce risk vulnerability	To what degree can the option reduce the likelihood and/or consequences of risks? Does the option reduce the number of people/systems exposed to a hazard?
(b) Enhance social wellbeing	Does the option contribute to reducing inequalities? Does the option increase employment? Are different social groups and remote regions included in the option? Are there health and education benefits to be had from the option? Does the option compromise the ability of future generations to meet their own needs in any way?
(c) Improve environment	Does the option enhance supporting, regulating or provisioning ecosystem services in any way? Does the option enhance the ability of systems, institutions and humans to adjust to potential damage, take advantage of opportunities, or respond to consequences? Does the option contribute to resilience building (ability to cope with stressors and reorganise to maintain structures and functions, retain capacity to transform)? Does the option enhance climate mitigation (e.g., carbon stocks through forest restoration)?
(d) Increase economic resources	Does the option increase profitability for/raise income of adopters (by increasing productivity or reducing the effective costs of inputs)? Does the option contribute to greater GDP or reduced inflation?
(e) Strengthen institutions	Would the option lead to transparency challenges? Is it difficult to account for the changes and for responsible implementation?
Maladaptive	Would the option lead to maladaptation?

SM5.7.2 Adaptation Options and Article Collection

Our selection started from a list of 69 adaptation options, grouped into 15 adaptation categories (Table SM 5.15), and narrowed in on those options most prolific in the literature and relevant based on expert assessment, and that were not being assessed in other chapters. We focused on currently implemented adaptation options in systems/sectors such as crop-based, livestock, fisheries, aquaculture, forestry, crop–livestock mixed, and supply chains, but water management such as improved irrigation efficiency and integrated water management was excluded because Chapter 4 extensively covered these options for agricultural sectors. Projected studies using modelling were excluded, since we focused on empirical studies of currently implemented options.

A literature search was conducted through SCOPUS and Web of Science for peer-reviewed articles published since 2014 using the following basic search terms:

'Climate change' OR 'global warming' OR 'climate variability' OR 'climate risk' AND adapt* OR adjust* OR alteration OR shift, combined with keywords for important adaptation option.

These general searches resulted in many references, but most of them were not relevant to the feasibility and effectiveness assessment. We, therefore, performed additional focused searches using guiding questions for feasibility and effectiveness indicators through SCOPUS, Web of Knowledge or Google Scholar. We selected studies from the search results if they considered the option in relation to climate change adaptation and contained evidence to answer guiding questions considered, resulting in a total of 287 studies for 15 adaptation options (Table SM.5.16).

Table SM5.15 | Adaptation categories and options in different systems initially considered in Chapter 5.

Systems/sectors	Adaptation category	Adaptation option
Cross-sectoral	Livelihood diversification	Migration (for off-farm employment, either seasonal or permanent)
Cross-sectoral		Diversification of livelihoods (economic diversification, either on-farm or employment in local community)
Consumption and nutrition	Consumer-side behaviour change	Dietary changes
Post-harvest		Reduce food waste (retailer and consumer)
Post-harvest		Packaging changes
Cross-sectoral	Climate services	Improving weather forecasting and early warning systems
Crop-based systems	Agronomic management (farm level)	No till, reduced tillage or conservation agriculture
Crop-based systems		Precision fertilizer management
Crop-based systems		Integrated pest and weed management
		Organic management
Cross-sectoral	Water management (farm level)	Improved irrigation efficiency and use
Crop-based systems		Drip irrigation
Crops–mixed–livestock–aquaculture–fisheries		Integrated water management/water conservation and efficiency
Aquaculture		Climate-smart facilities (e.g., deeper ponds, water storage)
Cross-sectoral (or one sector)	Water management (regional level)	
Crops–mixed–livestock–aquaculture–forestry–fisheries	Genetic improvement	Conventional breeding (cultivar or species improvement, assisted evolution in fisheries)
Crops–mixed–livestock–aquaculture–forestry–fisheries		Biotech and bioengineering
Fisheries (oceans and inland)	Infrastructure	Soft engineering responses and buffers
Aquaculture		Investment in protection infrastructure
Aquaculture		Greater investments in stronger equipment (i.e., cage and mooring systems)

Systems/sectors	Adaptation category	Adaptation option
Post-harvest		Food storage infrastructures
Post-harvest		Improved food transport and distribution
Post-harvest		Improved efficiency and sustainability of food processing, retail and agrifood industries
Post-harvest		Improved efficiency and sustainability of food processing, retail and agrifood industries; including reducing post-harvest losses
Mixed systems		Urban and peri-urban agriculture
Crops–mixed–livestock–aquaculture–forestry–fisheries	Agricultural diversification	Agricultural diversification landscape
Crops–mixed–livestock–aquaculture–forestry–fisheries		Agricultural diversification on-farm biodiversity (i.e., intercropping)
Crops–mixed–livestock–aquaculture–forestry–fisheries		Mixed systems: crops, trees, silvopastoral, fisheries, aquaculture, agroforestry
Crops–mixed–livestock–aquaculture–forestry–fisheries		Agroecological approaches at multiple scales
Crops–mixed–livestock–aquaculture–forestry–fisheries	Shift in production timing/location/species/density	Shifting location of crop production, grazing; relocation of aquatic species
Crop-based systems		Adjustment of planting dates/counter-season crop production
Crops–mixed–livestock–aquaculture–forestry–fisheries		Substitution/change plant or animal type
Aquaculture systems		Farmed stocks adjusted to the new productive capacity
Aquaculture systems		Change production cycle or aquaculture system type
Crop-based systems	Reduced land degradation; soil conservation and improvement; carbon capture	Reduced grassland conversion to cropland
Forest		Reduced deforestation and forest degradation
Forest		Reforestation and forest restoration
Forest		Afforestation and land rehabilitation
Forest		Reduced-impact logging
Crops–mixed–livestock–forestry		Improved soil management (reduced soil erosion, salinisation, compaction)
Crops–mixed–livestock–forestry		Increased organic carbon content, e.g., biochar, residues
Livestock–mixed	Livestock management	Livestock fattening
Livestock–mixed		Seasonal feed supplementation
Livestock–mixed		Improved animal health and parasites control
Livestock–mixed		Thermal stress control
Livestock–mixed		Methane inhibitors
Livestock–mixed		Organic management
Cross-sectoral (or one sector)	Policy and planning	Community-based adaptation (including disaster risk management)
Cross-sectoral (or one sector)		Local governance and conflict resolutions schemes

Systems/sectors	Adaptation category	Adaptation option
Cross-sectoral (or one sector)		National and international adaptation planning, coordination, policy and governance
Cross-sectoral (or one sector)		Improving access to community services, social assistance + social insurance
Cross-sectoral (or one sector)		Social safety nets (e.g., conditional cash transfers)
Cross-sectoral [or one sector]		Relocation of farming facilities
Post-harvest consumption/ nutrition		Increased food safety and quality monitoring
Cross-sectoral		Regional and local food systems strengthening
Cross-sectoral	Market-based strategies	Certification and labelling programmes
Cross-sectoral		Increase incentive to consume and farm non-feed species
Cross-sectoral		Transparency of food chains and external costs
Cross-sectoral		Shortening supply chains, direct sales, circular economies
Cross-sectoral		Farmer cooperatives, collective marketing
Cross-sectoral		Insurance products: weather index, aquaculture, etc.
Post-harvest		Bioeconomy (e.g., energy from waste)
Cross-sectoral	Collective resource management	Social support networks
Crops–mixed–livestock		Community seed/feed/fodder banks
Aquaculture systems		Collective water storage and management schemes (water use efficiency, WUE)
Cross-sectoral		Farmer-to-farmer training, farmer field schools
Forest		Community forest management
Cross-sectoral	Food system transformations	Food sovereignty, agroecology, right-to-food approaches
Cross-sectoral		Integrated approaches at multiple scales
Cross-sectoral		Addressing inequality (e.g., gender, Indigenous people)

Table SM5.16 | Number of studies selected for feasibility and effectiveness analysis in Chapter 5 by different regions and adaptation options.

Adaptation category	Adaptation option	Africa	Asia	Australasia	Central and South America	Europe	North America	Small Islands	Global	Total
Agricultural diversification	Agricultural diversification on-farm biodiversity (i.e., intercropping)	7	12		3		2		1	25
	Agricultural diversification landscape	7	1		5	4	1		4	22
	Mixed systems: crops, trees, silvopastoral, fisheries, aquaculture, agroforestry	19	12		2	3	1		3	40
	Agroecological approaches at multiple scales	3	2		2			2	2	11
Agronomic management (farm level)	Organic management	1	1		1	2	3		4	12
	Integrated pest and weed management					1				1

Adaptation category	Adaptation option	Africa	Asia	Australasia	Central and South America	Europe	North America	Small Islands	Global	Total
Climate services	Improving weather forecasting and early-warning systems	24	8		5		1			38
Collective resource management	Community forest management	3	12		2	1	3	1		22
	Community seed/feed/fodder banks	1	2		2				2	7
	Adaptive co-management			1						1
	Social support networks		1							1
	Harvester-driven conservation efforts						1			1
Genetic improvement	Conventional breeding (cultivar or species improvement, assisted evolution in fisheries)	5	2		1				2	10
	Biotech and bioengineering		1						1	2
Livelihood diversification	Diversification of livelihoods (economic diversification, either on-farm or employment in local community)	3	8	1	2		1	1	3	19
	Migration (for off-farm employment, either seasonal or permanent)		1							1
Policy and planning	Community-based adaptation (including disaster risk management)	2	5		1		8	3		19
	Local governance and conflict resolutions schemes		5		2	1	5		2	15
	Regional and local food systems strengthening	1		1	1	1	2	1		7
	Urban and peri-urban agriculture					1				1
	Shortening supply chains, direct sales, circular economies						1			1
	Improving access to community services, social assistance + social insurance		1							1
Shift in production timing/location/species/density	Substitution/change plant or animal type	12	6		1	2				21
	Adjustment of planting dates/ counter-season crop production		3						1	4
	Shifting location of crop production, grazing; relocation of aquatic species								1	1
Food system transformations	Integrated approaches at multiple scales	1								1
	Shortening supply chains, direct sales, circular economies					1				1
Reduced land degradation; soil conservation and improvement; carbon capture	Reduced deforestation and forest degradation		1							1
	Improved soil management (reduced soil erosion, salinisation, compaction)		1							1
Total		89	85	3	30	17	29	8	26	287

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SM5.7.3 Assessment Process

We followed the assessment method by Singh et al. (2020) with some modifications. We examined evidence for each indicator (guiding question) for each study for traceability. For the feasibility assessment, the following coding was applied:

i) the indicator potentially blocks the feasibility
ii) the indicator has some effect on the feasibility, or the evidence is mixed
iii) the indicator does not pose barriers to the feasibility
LE: the study has limited evidence
NE: the study has no evidence
NA: not applicable

Likewise, effectiveness was assessed as:

i) the option does not increase the effectiveness
ii) the option has some effect, or the evidence is mixed
iii) the option is effective
LE: the study has limited evidence
NE: the study has no evidence
NA: not applicable

The following score was assigned to each code, and the score was averaged for each indicator and each option.

A=1, B=2, and C=3

We considered that indicators had sufficient evidence if the number of assessed papers is five or more. Two reviewers assessed each study, and if the coding differed, they reconciled based on the evidence each study provided.

SM5.7.4 Data Distribution and Limitations

The selected studies covered all IPCC regions, but about 60% were from Africa and Asia, and less than 4% were from Australia and small islands (Table SM5.16). Among adaptation categories, agricultural diversification had the largest share (34%), followed by policy and planning (15%), climate services (13%) and collective resource management (11%). There were few studies on genetic improvement or agronomic management, partly because we excluded projected studies using crop simulation models, and the number of examiners was low. Five adaptation categories out of 15 were not included in our assessment. Because these studies were not selected through a systematic literature search, they are not a good representation of the literature available. Nevertheless, some adaptation categories had limited or no literature available, which highlighted a large research gap in our assessment of the feasibility and effectiveness of the adaptation options. They include those related to consumer-side behaviour change, infrastructure, livestock and market-based strategies.

We focused our research on currently implemented adaptation options, despite the vast literature available from simulation studies. Consequently, effectiveness measures are limited to current climate hazards, which may not be efficient under future climatic conditions. We evaluated micro- and macroeconomic viability, but studies including cost–benefit analyses were few, limiting our opportunities to assess economic feasibility. A part of these limitations can be partially overcome by leveraging a systematic literature review, but the fundamental challenges are limited studies conducted for multiple benefits from adaptation options, particularly those implemented beyond farmgate.

Table SM5.17 | References selected for the adaptation feasibility and effectiveness analysis in Chapter 5.

Adaptation category	Adaptation options	References
Agricultural diversification	Agricultural diversification on-farm biodiversity (i.e., intercropping)	Dillon et al. (2015); McCord et al. (2015); Makate et al. (2016); Gunathilaka et al. (2018); Roesch-McNally et al. (2018); Adhikari et al. (2019); Aniah et al. (2019); Bonifacio (2019); Dhakal and Kattel (2019); Maikhuri et al. (2019); Ravera et al. (2019); Bowles et al. (2020); Dutta et al. (2020); Fatima et al. (2020); Ndalilo et al. (2020); Singh et al. (2020b); Song et al. (2020b); Van Huynh et al. (2020); Assefa et al. (2021); Camacho-Villa et al. (2021); Chaudhary et al. (2021); Mzyece and Ng'ombe (2021); Novotny et al. (2021); Son et al. (2021); Theodory (2021)
	Agricultural diversification landscape	Estrada-Carmona et al. (2014); Harvey et al. (2014); Salton et al. (2014); Jönsson et al. (2015); Schroth et al. (2015); Douxchamps et al. (2016); Belay et al. (2017); Gil et al. (2017); Paul et al. (2017); Reed et al. (2017); Thom et al. (2017); Blaser et al. (2018); Burchfield and Poterie (2018); Maggio et al. (2018); Bozzola and Smale (2020); Frei et al. (2020); Ochieng et al. (2020); Piedra-Bonilla et al. (2020); Redhead et al. (2020); Remeš et al. (2020); Duncan et al. (2021); Onyeneke (2021)
	Mixed systems: crops, trees, silvopastoral, fisheries, aquaculture, agroforestry	De Zoysa and Inoue (2014); Lasco et al. (2014a); Lasco et al. (2014b); Linger (2014); Mbow et al. (2014a); Mbow et al. (2014b); Nasielski et al. (2015); Lasco et al. (2016); Newaj et al. (2016); Bunting et al. (2017); Hernández-Morcillo et al. (2017); Paul et al. (2017); Quandt et al. (2017); Abdulai et al. (2018a); Abdulai et al. (2018b); Apuri et al. (2018); Borremans et al. (2018); Sida et al. (2018); Ahmed et al. (2019); Aryal et al. (2019); Córdova et al. (2019); De Giusti et al. (2019); Dubois et al. (2019); Oduniyi and Tekana (2019); Paudel et al. (2019); Quandt et al. (2019); Rosa-Schleich et al. (2019); Freed et al. (2020); Gusli et al. (2020); Nyong et al. (2020); Papa et al. (2020); Quandt (2020); Reppin et al. (2020); Tran et al. (2020); Tschora and Cherubini (2020); Jha et al. (2021); Kais and Islam (2021); Pello et al. (2021); Reyes et al. (2021)
	Agroecological approaches at multiple scales	Calderón et al. (2018); Ticktin et al. (2018); Bezner Kerr et al. (2019); Aguilera et al. (2020); Bharucha et al. (2020); Buckwell et al. (2020); Cáceres-Arteaga et al. (2020); How et al. (2020); Nyantakyi-Frimpong (2020); Snapp et al. (2021)
Agronomic management (farm level)	Organic management	Skinner et al. (2014); Jacobi et al. (2015c); Bandanaa et al. (2016); Arbenz et al. (2017); Colting-Pulumbarit et al. (2018); Knapp and van der Heijden (2018); Röös et al. (2018); Schrama et al. (2018); Li et al. (2019c); Seipel et al. (2019); Eeswaran et al. (2021); Sanford et al. (2021)
	Integrated pest and weed management	Subramanian et al. (2016)

Adaptation category	Adaptation options	References
Climate services	Improving weather forecasting and early-warning systems	Furman et al. (2014); Gbetibouo et al. (2017); Amarnath et al. (2018); Dayamba et al. (2018); Loboguerrero et al. (2018); McKune et al. (2018); Balehegn et al. (2019); Clarkson et al. (2019); Daly and Dilling (2019); Grey (2019); Haines (2019); Iticha and Husen (2019); Naab et al. (2019); Nyantakyi-Frimpong (2019); Radeny et al. (2019); Spear et al. (2019); Tume et al. (2019); Ubisi et al. (2019); Diouf et al. (2020); Ebhuoma (2020); Hosen et al. (2020); Mogomotsi et al. (2020); Nidumolu et al. (2020); Nkuba et al. (2020); Partey et al. (2020); Rossa et al. (2020); Sotelo et al. (2020); Van Huynh et al. (2020); Camacho-Villa et al. (2021); Chaudhary et al. (2021); Henriksson et al. (2021); Nidumolu et al. (2021); Ofoegbu and New (2021); Pauli et al. (2021); Ruzol et al. (2021); Son et al. (2021)
Collective resource management	Community forest management	Bhatta et al. (2015); Chomba et al. (2015); Furness et al. (2015); Kongsager and Corbera (2015); Morin et al. (2015); Moktan et al. (2016); Barnes et al. (2017); Persson and Prowse (2017); Gustafson et al. (2018); Khadka et al. (2018); Sapkota et al. (2018); Amanuel et al. (2019); Clare et al. (2019); Lin et al. (2019); Ofoegbu et al. (2019); Silwal et al. (2019); Bhattarai (2020); Buckwell et al. (2020); Dhungana et al. (2020); Millner et al. (2020); Sansilvestri et al. (2020); Pathak et al. (2021)
	Community seed/feed/fodder banks	Bordoni and Hodgkin (2015); Galluzzi et al. (2015); Hunduma and Ortiz (2015); Vernooy et al. (2017); Arce et al. (2018); Maharjan and Maharjan (2018); Otieno et al. (2021)
	Adaptive co-management	Ogier et al. (2016)
	Social support networks	Mohamed Shaffril et al. (2019)
	Harvester-driven conservation efforts	Le Bris et al. (2018)
Genetic improvement	Conventional breeding (cultivar or species improvement, assisted evolution in fisheries)	Fisher et al. (2015); Fisher and Carr (2015); Sutcliffe et al. (2016); Williams and Carrico (2017); Wossen et al. (2017); Fatima et al. (2020); Tan et al. (2020); Gallardo-Hidalgo et al. (2021); Teeken and Temudo (2021); Zhang et al. (2021)
	Biotech and bioengineering	Nguyen (2016; Tan et al. (2020)
Livelihood diversification	Diversification of livelihoods (economic diversification, either on-farm or employment in local community)	Pandey et al. (2016); Adhikari et al. (2018); Galappaththi et al. (2019); Islam and Ghosh (2019); Mohamed Shaffril et al. (2019); Nursey-Bray et al. (2019); Utete et al. (2019); Dutta et al. (2020); Martins and Gasalla (2020); Mohamed Shaffril et al. (2020); Silas et al. (2020); Bacon et al. (2021); Mbah et al. (2021); Mulyasari et al. (2021); Oyebola et al. (2021); Pinsky et al. (2021); Schlingmann et al. (2021); von Seggern (2021)
	Migration (for off-farm employment, either seasonal or permanent)	Mohamed Shaffril et al. (2019)
Policy and planning	Community-based adaptation (including disaster risk management)	Alauddin and Sarker (2014); Galappaththi et al. (2016); Amare et al. (2018); Barua and Rahman (2019); Galappaththi et al. (2019); Lavoie et al. (2019); Roux et al. (2019); Basel et al. (2020); Bronen et al. (2020); Chen and Cheng (2020); Galappaththi et al. (2020); Martins and Gasalla (2020); Pearson et al. (2020); Schott et al. (2020); Sowman (2020); Berkes (2021); de Scally and Doberstein (2021); Galappaththi et al. (2021)
	Local governance and conflict resolutions schemes	Burden and Fujita (2019); Galappaththi et al. (2019); Suasi and Koya (2019); Tilley et al. (2019); Tran et al. (2019); Galappaththi et al. (2020); Islam et al. (2020); Kyvelou and Ierapetritis (2020); McClenachan et al. (2020); Millin (2020); Schott et al. (2020); Whitney et al. (2020); Berkes (2021); Casagrande et al. (2021); Gianelli et al. (2021)
	Regional and local food systems strengthening	Chapin et al. (2016); Karg et al. (2016); Dubbeling et al. (2017); Berner et al. (2019); Ballamingie et al. (2020); Hickey and Unwin (2020); Canal Vieira et al. (2021)
	Urban and peri-urban agriculture	Grafius et al. (2020)
	Shortening supply chains, direct sales, circular economies	Lengnick et al. (2015)
	Improving access to community services, social assistance + social insurance	Mohamed Shaffril et al. (2019)
Shift in production timing/location/species/density	Substitution/change plant or animal type	Menike and Arachchi (2016); Ndamani and Watanabe (2016); Kabir et al. (2017); Tabbo and Amadou (2017); Delaporte and Maurel (2018); Cuni-Sanchez et al. (2019); Larbi et al. (2019); Lemessa et al. (2019); Makate et al. (2019); Rodríguez et al. (2019); Tongruksawattana and Wainaina (2019); Acevedo et al. (2020); Guodaar et al. (2020); Markou et al. (2020); Zhang et al. (2020); Azumah et al. (2021); Wordofa et al. (2021)
	Shifting location of crop production, grazing; relocation of aquatic species	Bell et al. (2020)
	Adjustment of planting dates/ counter-season crop production	Wang et al. (2015b); Xiao et al. (2016); Fatima et al. (2020); Zhang et al. (2020)
Food system transformations	Integrated approaches at multiple scales	Makondo and Thomas (2018)
	Shortening supply chains, direct sales, circular economies	Sellberg et al. (2020)
Reduced land degradation; soil conservation and improvement; carbon capture	Reduced deforestation and forest degradation	Newton et al. (2015)
	Improved soil management (reduced soil erosion, salinisation, compaction)	Arshad et al. (2021)

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