13SM

Europe
Supplementary Material

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Table of Contents

SM13.1 Supplementary Material Supporting Section 13.2 3

SM13.2 Supplementary Material Supporting Section 13.3 8

SM13.3 Supplementary Material Supporting Section 13.4 10

SM13.4 Supplementary Material Supporting Section 13.5 11

SM13.5 Supplementary Material Supporting Section 13.6 14

SM13.6 Supplementary Material Supporting Section 13.7 32

SM13.7 Supplementary Material Supporting Section 13.8 33

SM13.8 Supplementary Material Supporting Section 13.10 34

SM13.9 Supplementary Material Supporting the Feasibility and Effectiveness Assessment 36

SM13.10 Supplementary Material Supporting the Key Risks and Burning Embers Assessments 36

SM13.11 Supplementary Material Supporting the Development of Adaptation Pathways 48

References 49

SM13.1 Supplementary Material Supporting Section 13.2

Table SM13.1 | Literature sources used in the assessment of feasibility and effectiveness of adaptation options for water systems in Europe (Figure 13.6)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Coastal and riverine flooding	Flood defences (Protect)	Andersson-Sköld et al. (2015); Alfieri et al. (2016a); Bollinger and Dijkema (2016); Bouwer et al. (2018); Metin et al. (2018); Pérez-Morales et al. (2018); Thacker et al. (2018); EEA (2019c); Straatsma et al. (2019); Dottori et al. (2020); Vousdoukas et al. (2020); Umgiesser et al. (2021)	Alfieri et al. (2016a); Bollinger and Dijkema (2016); Bouwer et al. (2018); Pérez-Morales et al. (2018); Thacker et al. (2018); EEA (2019c); EEA (2019a); Vousdoukas et al. (2020)	Metin et al. (2018); Thacker et al. (2018); Straatsma et al. (2019); Vousdoukas et al. (2020)	Bollinger and Dijkema (2016); Bubeck et al. (2017); Thacker et al. (2018); EEA (2019c); EEA (2019a)	Alfieri et al. (2016a)	Andersson-Sköld et al. (2015); Del Bello (2018); Pérez-Morales et al. (2018); Vousdoukas et al. (2020)	Del Bello (2018); EEA (2019a); Straatsma et al. (2019)
	Flood preparedness and early warning plans (Protect/ Accommodate)	Poussin et al. (2013); Kreibich et al. (2015); Pappenberger et al. (2015); Bubeck et al. (2017); Kreibich et al. (2017); Pérez-Morales et al. (2018); Restemeyer et al. (2018); Varrani and Nones (2018); Adedeji et al. (2019); Merz et al. (2020); Pirlone et al. (2020); Ribas et al. (2020); Kreibich et al. (2021)	Poussin et al. (2013); Kreibich et al. (2015); Pappenberger et al. (2015); Bubeck et al. (2017); Kreibich et al. (2017); Pérez-Morales et al. (2018); Restemeyer et al. (2018); Varrani and Nones (2018); Adedeji et al. (2019); Merz et al. (2020); Pirlone et al. (2020); Ribas et al. (2020); Kreibich et al. (2021)	Poussin et al. (2013); Kreibich et al. (2015); Pappenberger et al. (2015); Bubeck et al. (2017); Kreibich et al. (2017); Pérez-Morales et al. (2018); Restemeyer et al. (2018); Varrani and Nones (2018); Adedeji et al. (2019); Merz et al. (2020); Pirlone et al. (2020); Ribas et al. (2020); Kreibich et al. (2021)	Poussin et al. (2013); Kreibich et al. (2015); Pappenberger et al. (2015); Bubeck et al. (2017); Kreibich et al. (2017); Pérez-Morales et al. (2018); Restemeyer et al. (2018); Varrani and Nones (2018); Adedeji et al. (2019); Merz et al. (2020); Pirlone et al. (2020); Ribas et al. (2020); Kreibich et al. (2021)	Poussin et al. (2013); Kreibich et al. (2015); Bubeck et al. (2017); Kreibich et al. (2017); Pérez-Morales et al. (2018); Restemeyer et al. (2018); Varrani and Nones (2018); Adedeji et al. (2019); Merz et al. (2020); Pirlone et al. (2020); Ribas et al. (2020); Kreibich et al. (2021)	Poussin et al. (2013); Kreibich et al. (2015); Pappenberger et al. (2015); Bubeck et al. (2017); Kreibich et al. (2017); Pérez-Morales et al. (2018); Restemeyer et al. (2018); Varrani and Nones (2018); Adedeji et al. (2019); Merz et al. (2020); Pirlone et al. (2020); Ribas et al. (2020); Kreibich et al. (2021)	Poussin et al. (2013); Kreibich et al. (2015); Pappenberger et al. (2015); Bubeck et al. (2017); Kreibich et al. (2017); Pérez-Morales et al. (2018); Restemeyer et al. (2018); Varrani and Nones (2018); Adedeji et al. (2019); Merz et al. (2020); Pirlone et al. (2020); Ribas et al. (2020); Kreibich et al. (2021)
	Planned relocation (Retreat)	Koerth et al. (2013); Harman et al. (2015); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Buser (2020); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Seebauer and Winkler (2020); Thaler (2021)	Koerth et al. (2013); Harman et al. (2015); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Buser (2020); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Seebauer and Winkler (2020); Thaler (2021)	Koerth et al. (2013); Harman et al. (2015); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Seebauer and Winkler (2020); Thaler (2021)	Koerth et al. (2013); Harman et al. (2015); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Buser (2020); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Seebauer and Winkler (2020); Thaler (2021)	Koerth et al. (2013); Harman et al. (2015); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Buser (2020); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Seebauer and Winkler (2020); Thaler (2021)	Koerth et al. (2013); Harman et al. (2015); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Seebauer and Winkler (2020); Thaler (2021)	Koerth et al. (2013); Harman et al. (2015); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Buser (2020); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Seebauer and Winkler (2020); Thaler (2021)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Coastal and riverine flooding	No-build zone, restrict new developments (Avoidance)	Koerth et al. (2013); Andersson-Sköld et al. (2015); Harman et al. (2015); Thieken et al. (2016); Pérez-Morales et al. (2018); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Thaler (2021)	Koerth et al. (2013); Andersson-Sköld et al. (2015); Harman et al. (2015); Thieken et al. (2016); Pérez-Morales et al. (2018); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Thaler (2021)	Koerth et al. (2013); Andersson-Sköld et al. (2015); Harman et al. (2015); Thieken et al. (2016); Pérez-Morales et al. (2018); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Thaler (2021)	Koerth et al. (2013); Andersson-Sköld et al. (2015); Harman et al. (2015); Thieken et al. (2016); Pérez-Morales et al. (2018); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Thaler (2021)		Koerth et al. (2013); Andersson-Sköld et al. (2015); Harman et al. (2015); Thieken et al. (2016); Pérez-Morales et al. (2018); Thacker et al. (2018); Dachary-Bernard et al. (2019); Hofstede (2019); Rey-Valette et al. (2019); Dottori et al. (2020); Lincke et al. (2020); Mayr et al. (2020); Thaler (2021)	
	Flood insurance (Supporting)	Koerth et al. (2013); Poussin et al. (2013); Keskitalo et al. (2014); Paudel et al. (2015); Penning-Rowsell and Priest (2015); Surminski et al. (2015); Hudson et al. (2016); O'Hare et al. (2016); Suykens et al. (2016); Surminski and Thieken (2017); Hanger et al. (2018); Hudson (2018); Surminski (2018)	Koerth et al. (2013); Poussin et al. (2013); Keskitalo et al. (2014); Paudel et al. (2015); Penning-Rowsell and Priest (2015); Surminski et al. (2015); Hudson et al. (2016); O'Hare et al. (2016); Suykens et al. (2016); Surminski and Thieken (2017); Hanger et al. (2018); Hudson (2018); Surminski (2018)	Koerth et al. (2013); Poussin et al. (2013); Keskitalo et al. (2014); Paudel et al. (2015); Penning-Rowsell and Priest (2015); Surminski et al. (2015); Hudson et al. (2016); O'Hare et al. (2016); Suykens et al. (2016); Surminski and Thieken (2017); Hanger et al. (2018); Hudson (2018); Surminski (2018)	Koerth et al. (2013); Poussin et al. (2013); Keskitalo et al. (2014); Paudel et al. (2015); Penning-Rowsell and Priest (2015); Surminski et al. (2015); Hudson et al. (2016); O'Hare et al. (2016); Suykens et al. (2016); Surminski and Thieken (2017); Hanger et al. (2018); Hudson (2018); Surminski (2018)	Koerth et al. (2013); Poussin et al. (2013); Keskitalo et al. (2014); Paudel et al. (2015); Penning-Rowsell and Priest (2015); Surminski et al. (2015); Hudson et al. (2016); O'Hare et al. (2016); Suykens et al. (2016); Surminski and Thieken (2017); Hanger et al. (2018); Hudson (2018); Surminski (2018)	Koerth et al. (2013); Poussin et al. (2013); Keskitalo et al. (2014); Paudel et al. (2015); Penning-Rowsell and Priest (2015); Surminski et al. (2015); Hudson et al. (2016); O'Hare et al. (2016); Suykens et al. (2016); Surminski and Thieken (2017); Hanger et al. (2018); Hudson (2018); Surminski (2018)	
Coastal flooding	Wet and dry proofing (Accommodate)	Botzen et al. (2013); Poussin et al. (2015); Stojanov et al. (2015); Bouwer et al. (2018); Hudson et al. (2019)	Botzen et al. (2013); Poussin et al. (2015); Stojanov et al. (2015); Bouwer et al. (2018); Hudson et al. (2019)		Botzen et al. (2013); Poussin et al. (2015); Stojanov et al. (2015); Bouwer et al. (2018); Hudson et al. (2019)	Botzen et al. (2013); Stojanov et al. (2015)		
	Sediment based (e.g., nourishment) (Protect)	Campos et al. (2016)	Temmerman et al. (2013); Campos et al. (2016); de Schipper et al. (2021); Staudt et al. (2021)	Temmerman et al. (2013); Campos et al. (2016); de Schipper et al. (2021); Staudt et al. (2021)	Campos et al. (2016); de Schipper et al. (2021); Staudt et al. (2021)	Temmerman et al. (2013); de Schipper et al. (2021); Staudt et al. (2021)	Temmerman et al. (2013); Parkinson and Ogurcak (2018); de Schipper et al. (2021); Staudt et al. (2021)	Parkinson and Ogurcak (2018); Staudt et al. (2021)
	Ecosystem based (e.g., wetlands, dunes) (Protect)	Temmerman et al. (2013); Narayan et al. (2016); Vuik et al. (2019)	Temmerman et al. (2013); Narayan et al. (2016); Vuik et al. (2019)	Temmerman et al. (2013); Narayan et al. (2016); Vuik et al. (2019)			Temmerman et al. (2013); Narayan et al. (2016); Vuik et al. (2019)	Temmerman et al. (2013); Vuik et al. (2019)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Riverine flooding	Wet and dry proofing (Accommodate)	Hudson et al. (2014); Kreibich et al. (2015); Poussin et al. (2015); Jones et al. (2017); Osberghaus (2017); Bouwer et al. (2018); Salinas-Rodriguez et al. (2018); Thacker et al. (2018); Haer et al. (2019); Hudson et al. (2019); Sairam et al. (2019)	Osberghaus (2017); Thacker et al. (2018)	Botzen et al. (2013); Hudson et al. (2014); Kreibich et al. (2015); Poussin et al. (2015); Stojanov et al. (2015); Jones et al. (2017); Osberghaus (2017); Bouwer et al. (2018); Salinas-Rodriguez et al. (2018); Thacker et al. (2018); Haer et al. (2019); Hudson et al. (2019); Sairam et al. (2019)	Botzen et al. (2013); Hudson et al. (2014); Kreibich et al. (2015); Poussin et al. (2015); Stojanov et al. (2015); Jones et al. (2017); Osberghaus (2017); Bouwer et al. (2018); Salinas-Rodriguez et al. (2018); Thacker et al. (2018); Haer et al. (2019); Hudson et al. (2019); Sairam et al. (2019)	Botzen et al. (2013); Stojanov et al. (2015); Osberghaus (2017)		Jones et al. (2017)
	Ecosystem based (e.g., floodplain restoration, widening riverbed) (Protect)	Dadson et al. (2017); Straatsma et al. (2019); Dottori et al. (2020)	Straatsma et al. (2019); Dottori et al. (2020)	Straatsma et al. (2019)		Straatsma et al. (2019); Dottori et al. (2020)		Asselman and Klijn (2016); Dadson et al. (2017); Straatsma et al. (2019); Dottori et al. (2020); European Commission (2020)
	Retention and diversion (Accommodate)	Gocht and Meon (2016); Dadson et al. (2017); Verkerk et al. (2017); Dottori et al. (2020)	Gocht and Meon (2016); Verkerk et al. (2017)	Gocht and Meon (2016); Verkerk et al. (2017)		Verkerk et al. (2017); Dottori et al. (2020)	Verkerk et al. (2017); Dottori et al. (2020)	
Pluvial flooding	Green roofs (Accommodate)	Andersson-Sköld et al. (2015); Zölch et al. (2017); Liu et al. (2018); Babovic and Mijic (2019)	Andersson-Sköld et al. (2015); Zölch et al. (2017); Liu et al. (2018); Babovic and Mijic (2019)	European Commission (2020)		Zölch et al. (2017)	Andersson-Sköld et al. (2015); Zölch et al. (2017)	Andersson-Sköld et al. (2015); Zölch et al. (2017); Liu et al. (2018); European Commission (2020)
	Retention parks (Accommodate)	Andersson-Sköld et al. (2015); Arnbjerg-Nielsen et al. (2015); Maragno et al. (2018); Salinas-Rodriguez et al. (2018); Ribas et al. (2020)		Maragno et al. (2018); Ribas et al. (2020)		Andersson-Sköld et al. (2015); Maragno et al. (2018)	Andersson-Sköld et al. (2015); Arnbjerg-Nielsen et al. (2015); Maragno et al. (2018); Salinas-Rodriguez et al. (2018); Ribas et al. (2020)	Andersson-Sköld et al. (2015); Arnbjerg-Nielsen et al. (2015); Maragno et al. (2018); Salinas-Rodriguez et al. (2018); Ribas et al. (2020)
	Update drainage system and pumps (Accommodate)	Skougaard Kaspersen et al. (2017)	Skougaard Kaspersen et al. (2017); Liu and Jensen (2018); EEA (2020b); Ribas et al. (2020)	Ribas et al. (2020)	Liu and Jensen (2018); EEA (2020b)	EEA (2020b)	EEA (2020b)	Liu and Jensen (2018); EEA (2020b)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Water scarcity	Supply: storage (i.e., reservoirs)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016); Varela-Ortega et al. (2016); Bucak et al. (2017); Verkerk et al. (2017); Di Baldassarre et al. (2018); Garnier and Holman (2019)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016); Varela-Ortega et al. (2016); Bucak et al. (2017); Verkerk et al. (2017); Di Baldassarre et al. (2018); Garnier and Holman (2019)	Papadaskalopoulou et al. (2015b); Varela-Ortega et al. (2016); Verkerk et al. (2017); Garnier and Holman (2019)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016); Varela-Ortega et al. (2016); Thacker et al. (2018); Garnier and Holman (2019)	Papadaskalopoulou et al. (2015b); Verkerk et al. (2017)	Papadaskalopoulou et al. (2015b); Varela-Ortega et al. (2016); Di Baldassarre et al. (2018); Santos et al. (2018); Garnier and Holman (2019)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016); Bucak et al. (2017); Di Baldassarre et al. (2018); Santos et al. (2018); Garnier and Holman (2019)
	Supply: water diversion and transfer	Fleskens et al. (2013); Collet et al. (2015); Papadaskalopoulou et al. (2015b)	Fleskens et al. (2013); Collet et al. (2015)	Fleskens et al. (2013); Collet et al. (2015); Papadaskalopoulou et al. (2015b)	Fleskens et al. (2013); Collet et al. (2015); Papadaskalopoulou et al. (2015b); Garnier and Holman (2019)	Fleskens et al. (2013); Papadaskalopoulou et al. (2015b)	Papadaskalopoulou et al. (2015b); Garnier and Holman (2019)	Collet et al. (2015)
	Supply: desalination	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016); Garnier and Holman (2019); Morote et al. (2019)	Papadaskalopoulou et al. (2015b); Garnier and Holman (2019); Morote et al. (2019)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016); Garnier and Holman (2019); Morote et al. (2019)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016); Garnier and Holman (2019); Morote et al. (2019)	Morote et al. (2019)	Papadaskalopoulou et al. (2015b); Morote et al. (2019) Morete et al. (2019); Papadaskalopoulou et al. (2015	Garnier and Holman (2019); Morote et al. (2019)
	Supply: water reuse	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016);Morote (2019); De Roo et al. (2020)	Papadaskalopoulou et al. (2015b); Morote et al. (2019)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016);Morote (2019); De Roo et al. (2020)	Papadaskalopoulou et al. (2015b); Kingsborough et al. (2016);Morote (2019)	Papadaskalopoulou et al. (2015b); Morote et al. (2019)	Papadaskalopoulou et al. (2015b); Morote et al. (2019)	Morote et al. (2019)
	Demand: water saving and efficiency	Collet et al. (2015); Papadaskalopoulou et al. (2015b); Fader et al. (2016); Kingsborough et al. (2016); Varela-Ortega et al. (2016); Iglesias et al. (2018); Manouseli et al. (2018); Papadimitriou et al. (2019); De Roo et al. (2020)	Papadaskalopoulou et al. (2015b); van Duinen et al. (2015); Fader et al. (2016); Kingsborough et al. (2016); Varela-Ortega et al. (2016); Rey et al. (2017); Iglesias et al. (2018); Manouseli et al. (2018)	Collet et al. (2015); Papadaskalopoulou et al. (2015b); van Duinen et al. (2015); Fader et al. (2016); Varela-Ortega et al. (2016); Rey et al. (2017); Verkerk et al. (2017); Iglesias et al. (2018); Manouseli et al. (2018)	Collet et al. (2015); Papadaskalopoulou et al. (2015b); Varela-Ortega et al. (2016); Verkerk et al. (2017); Papadimitriou et al. (2019)	Collet et al. (2015); Papadaskalopoulou et al. (2015b); Manouseli et al. (2018)	van Duinen et al. (2015); Fader et al. (2016); Varela-Ortega et al. (2016); Verkerk et al. (2017); Iglesias et al. (2018); Papadimitriou et al. (2019)	van Duinen et al. (2015); Papadimitriou et al. (2019)
	Demand: regulate distribution	Papadaskalopoulou et al. (2015b); Manouseli et al. (2018); Garnier and Holman (2019); Teotónio et al. (2020)	Papadaskalopoulou et al. (2015b); Garnier and Holman (2019); Teotónio et al. (2020)	Manouseli et al. (2018); Garnier and Holman (2019)	Papadaskalopoulou et al. (2015b); Manouseli et al. (2018); Garnier and Holman (2019); Teotónio et al. (2020)	Papadaskalopoulou et al. (2015b)		Manouseli et al. (2018); Garnier and Holman (2019); Teotónio et al. (2020)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Water scarcity	Demand: economic instruments	Kayaga and Smout (2014); Wimmer et al. (2014); Esteve et al. (2015); Kahil et al. (2015); Papadaskalopoulou et al. (2015b); Varela-Ortega et al. (2016); Koopman et al. (2017); Crespo et al. (2019)	Kayaga and Smout (2014); Esteve et al. (2015); Kahil et al. (2015); Papadaskalopoulou et al. (2015b); Varela-Ortega et al. (2016); Rey et al. (2017); Garnier and Holman (2019)	Wimmer et al. (2014); Esteve et al. (2015); Kahil et al. (2015); Papadaskalopoulou et al. (2015b); Varela-Ortega et al. (2016); Koopman et al. (2017); Crespo et al. (2019)	Esteve et al. (2015); Kahil et al. (2015); Papadaskalopoulou et al. (2015b); Varela-Ortega et al. (2016); Koopman et al. (2017); Crespo et al. (2019)	Kayaga and Smout (2014); Esteve et al. (2015); Kahil et al. (2015); Papadaskalopoulou et al. (2015b)	Esteve et al. (2015); Kahil et al. (2015); Varela-Ortega et al. (2016)	Esteve et al. (2015)
	Demand: land management and cover change	Papadaskalopoulou et al. (2015b); Carvalho-Santos et al. (2016); Varela-Ortega et al. (2016); Papadimitriou et al. (2019)	Carvalho-Santos et al. (2016); Varela-Ortega et al. (2016)	Carvalho-Santos et al. (2016); Varela-Ortega et al. (2016); Verkerk et al. (2017)	Varela-Ortega et al. (2016); Verkerk et al. (2017)	Garnier and Holman (2019)	Carvalho-Santos et al. (2016); Varela-Ortega et al. (2016); Verkerk et al. (2017); Papadimitriou et al. (2019)	Carvalho-Santos et al. (2016); Varela-Ortega et al. (2016); Verkerk et al. (2017); Garnier and Holman (2019); Papadimitriou et al. (2019)
	Monitoring and operational management, drought early warning systems	Papadaskalopoulou et al. (2015b)	Papadaskalopoulou et al. (2015b); Verkerk et al. (2017); Garnier and Holman (2019)	Papadaskalopoulou et al. (2015b)	Papadaskalopoulou et al. (2015b); Verkerk et al. (2017)	Verkerk et al. (2017)	Verkerk et al. (2017)	

SM13.2 Supplementary Material Supporting Section 13.3

Table SM13.2 | Literature sources used for assessment of major impacts on, and risks for, terrestrial and freshwater ecosystems in Europe for 1.5°C and 3°C GWL (Figure 13.8)

Terrestrial and freshwater ecosystems	Supporting references of assessment
Reduction in habitat availability of cold-adapted groups	Balint et al. (2011); Dornelas et al. (2014); Hodd et al. (2014); Hubble (2014); Kovats et al. (2014); Oliver et al. (2014); McGill et al. (2015); Oliver et al. (2015); Saltré et al. (2015); Talavera et al. (2015); Barredo et al. (2016); Coll et al. (2016); Hellmann et al. (2016); Jørgensen et al. (2016); Liverpool (2016); Dapporto et al. (2017); EEA (2017b); Vermaat et al. (2017); Ciscar et al. (2018); Hillebrand et al. (2018); Sirois-Delisle and Kerr (2018); Suggitt et al. (2018); Warren et al. (2018); Habel et al. (2019); Hinojosa et al. (2019); van Strien et al. (2019); Dullinger et al. (2020); Outhwaite et al. (2020); Soroye et al. (2020); Xi (2020); Carnicer et al. (2021)
Reduction in biodiversity of cold-adapted groups	Balint et al. (2011); Stefanescu et al. (2011); Dornelas et al. (2014); Oliver et al. (2014); Zografou et al. (2014); Hill and Preston (2015); McGill et al. (2015); Oliver et al. (2015); Talavera et al. (2015); Hellmann et al. (2016); Hendriks et al. (2016); Jørgensen et al. (2016); Rizzetto et al. (2016); Stephens et al. (2016); Vodă et al. (2016); Dapporto et al. (2017); EEA (2017b); Vermaat et al. (2017); Dyderski et al. (2018); Hillebrand et al. (2018); Sirois-Delisle and Kerr (2018); Spooner et al. (2018); Suggitt et al. (2018); Warren et al. (2018); Dennis et al. (2019); Habel et al. (2019); Herrando et al. (2019); Hinojosa et al. (2019); van Strien et al. (2019); Dullinger et al. (2020); Kougioumoutzis et al. (2020); Outhwaite et al. (2020); Soroye et al. (2020); Xi (2020)
Range shifts	Parmesan et al. (1999); Wilson et al. (2007); Devictor et al. (2008); Lenoir et al. (2008); Jiguet et al. (2010); Chen et al. (2011); Scherrer and Körner (2011); Devictor et al. (2012); De Frenne et al. (2013); Lenoir et al. (2013); Kovats et al. (2014); Bowler et al. (2015); Ancillotto et al. (2016); Jørgensen et al. (2016); Stephens et al. (2016); Wiens (2016); Bowler et al. (2017); EEA (2017b); Massimino et al. (2017); Mills et al. (2017); Pearce-Higgins et al. (2017); Sáenz-Romero et al. (2017); Bowler et al. (2018); Dyderski et al. (2018); Mori et al. (2018); Rumpf et al. (2018); Sirois-Delisle and Kerr (2018); Spooner et al. (2018); Steinbauer et al. (2018); Suggitt et al. (2018); Bowler et al. (2019); Carnicer et al. (2019b); Gómez (2019); Jaime et al. (2019); Lehikoinen et al. (2019a); Pérez Navarro et al. (2019); Post et al. (2019); Termaat et al. (2019); Vilà-Cabrera et al. (2019); Margalef-Marrase et al. (2020); Pavón-Jordán et al. (2020); Soroye et al. (2020); van Klink et al. (2020a); Zellweger et al. (2020); Urvois et al. (2021)
Changes in phenology	Ovaskainen et al. (2013); Thackeray et al. (2013); Frolov et al. (2014); Garonna et al. (2014); Karlsson (2014); Plard et al. (2014); Schröder et al. (2014); van Vliet et al. (2014); Fu et al. (2015); Gill et al. (2015); Malcolm et al. (2015); Roberts et al. (2015); Gaüzère et al. (2016); Newson et al. (2016); Szabó et al. (2016); Thackeray et al. (2016a); EEA (2017b); Gauzere et al. (2017); Glushenkov (2017); Güsewell et al. (2017); Halupka and Halupka (2017); Mayor et al. (2017); Miles et al. (2017); Prokosheva (2017); Wang et al. (2017a); Asse et al. (2018); Chen et al. (2018); Chizhikova (2018); Cohen et al. (2018b); Donnelly et al. (2018); Hidalgo-Galvez et al. (2018); Posledovich et al. (2018); Vitasse et al. (2018); Wu et al. (2018); Bobretsov et al. (2019); Fraga et al. (2019); Jakoby et al. (2019b); Lehikoinen et al. (2019a); Ma et al. (2019); Macgregor et al. (2019); Peaucelle et al. (2019); Piao et al. (2019); Prislan et al. (2019); Tishkov et al. (2019); Delgado et al. (2020); Menzel et al. (2020); Orellana-Macías et al. (2020); Wang et al. (2020); Keogan et al. (2021); Rosbakh et al. (2021)
Decrease in ecosystem production	Nabuurs et al. (2003); Ciais et al. (2005); Schröter et al. (2005); Smith et al. (2005); Reichstein et al. (2007); Schulze et al. (2009); Carnicer et al. (2011); Fantappié et al. (2011); Elmendorf et al. (2012); Carnicer et al. (2013); Coll et al. (2013); Peñuelas et al. (2013); Kovats et al. (2014); Ruiz-Benito et al. (2014); Schröter et al. (2014); Gazol et al. (2015); Keenan et al. (2016); Naudts et al. (2016); Novick et al. (2016); Polce et al. (2016); Schubert et al. (2016); Tian et al. (2016); van der Plas et al. (2016); Yigini and Panagos (2016); Ballantyne et al. (2017); Bright et al. (2017); EASAC (2017); EEA (2017b); Nabuurs et al. (2017); Peñuelas et al. (2017a); Peñuelas et al. (2017b); Ratcliffe et al. (2017); Schwalm et al. (2017); Teuling et al. (2017); Valade et al. (2017); Gazol et al. (2018); Humphrey et al. (2018); Lugato et al. (2018); Luyssaert et al. (2018); Nabuurs (2018); Sanginés de Cárcer et al. (2018); Stocker et al. (2018); Torralba et al. (2018); Verhagen et al. (2018); Carnicer et al. (2019a); Ciais et al. (2019); EASAC (2019); Fernández-Martínez et al. (2019); Green et al. (2019); Jaime et al. (2019); Lee et al. (2019); Natali et al. (2019); Pérez Navarro et al. (2019); Post et al. (2019); Stocker et al. (2019); Xu et al. (2019); Yuan et al. (2019); Zhou et al. (2019); Batllori et al. (2020); Brodribb et al. (2020); Ito et al. (2020); Krause et al. (2020); Lian et al. (2020); Margalef-Marrase et al. (2020); Schuldt et al. (2020); Wang (2020); Zhang et al. (2020); Canadell and Jackson (2021); Roces-Díaz et al. (2021); Yu et al. (2021)
Rising incidence of fire	Moriondo et al. (2006); Bondur (2011); Dury et al. (2011); Bedia et al. (2014); Turco et al. (2014); Drobyshev et al. (2015); Jolly et al. (2015); Tedim et al. (2015); Wu et al. (2015b); Drobyshev et al. (2016); Khabarov et al. (2016); Regos et al. (2016); Turco et al. (2016); Camia (2017); de Rigo et al. (2017); Forzieri et al. (2017); Fréjaville (2017); Ruffault et al. (2017); Sitnov et al. (2017); Turco et al. (2017); Bedia et al. (2018); Filipchuk et al. (2018); Lahaye et al. (2018); San-Miguel-Ayanz et al. (2018); Sitnov and Mokhov (2018); Turco et al. (2018a); Turco et al. (2018b); Chergui (2019); Michetti and Pinar (2019); Pausas (2019); Costa (2020); Di Giuseppe et al. (2020); Dupuy et al. (2020); Royé et al. (2020)
Reduced pollination services (reduction of regulating ecosystem services)	Menéndez et al. (2006); Roberts et al. (2011); Franzén and Öckinger (2012); Carvalheiro et al. (2013); Polce et al. (2014); Kaloveloni et al. (2015); Kerr et al. (2015); Rasmont et al. (2015); Tzilivakis et al. (2015); Ipbes (2016); Petz et al. (2016); Settele et al. (2016); Radenković et al. (2017); Marshall et al. (2018); Fourcade et al. (2019); Powney et al. (2019); Steele et al. (2019); Van Dooren (2019); Soroye et al. (2020); Zattara and Aizen (2020); Vasiliev and Greenwood (2021)
Increased soil erosion (reduction of regulating ecosystem services)	Bangash et al. (2013); Mezösi et al. (2013); Routschek et al. (2014); Anaya-Romero et al. (2015); Cilek et al. (2015); European Commission (2015); Panagos et al. (2015); Serpa et al. (2015); Sobol et al. (2015); Tzilivakis et al. (2015); Adler-Nissen (2016); Borrelli et al. (2016); Grossel et al. (2016); Guerra et al. (2016); Polce et al. (2016); Li et al. (2017); Litvin et al. (2017); Panagos et al. (2017); Prins et al. (2017); Chizhikova (2018); Gusarov et al. (2018); Auerswald and Fiener (2019); Mullan et al. (2019); Pastor et al. (2019a); Berberoglu et al. (2020); Borrelli et al. (2020); Ciampalini et al. (2020); Gianinetto et al. (2020); Gusarov (2020); Luetzenburg et al. (2020); Morán-Ordóñez et al. (2020); Rodrigues et al. (2020); Svetlitchnyi (2020)

Table SM13.3 | Percentage of species per group projected to remain within their suitable climate conditions (Figure 13.9)

Plants														
Regions	**1.5°C GWL**	**Std**		**2°C GWL**	**Std**		**2.7°C GWL**	**Std**		**3.2°C GWL**	**Std**		**4.5°C GWL**	**Std**
WCE	0.77	0.08		0.70	0.09		0.58	0.10		0.53	0.10		0.39	0.10
NEU	0.85	0.18		0.81	0.19		0.76	0.20		0.74	0.21		0.67	0.23
SEU	0.75	0.09		0.67	0.11		0.53	0.12		0.47	0.12		0.31	0.12
EEU	0.75	0.12		0.69	0.13		0.58	0.14		0.52	0.15		0.35	0.14
Insects														
Regions	**1.5°C GWL**	**Std**		**2°C GWL**	**Std**		**2.7°C GWL**	**Std**		**3.2°C GWL**	**Std**		**4.5°C GWL**	**Std**
WCE	0.59	0.11		0.49	0.11		0.34	0.11		0.29	0.10		0.17	0.08
NEU	0.90	0.14		0.86	0.18		0.76	0.25		0.72	0.28		0.58	0.34
SEU	0.65	0.13		0.56	0.15		0.43	0.17		0.38	0.17		0.26	0.15
EEU	0.72	0.15		0.64	0.18		0.49	0.20		0.42	0.21		0.25	0.19
Pollinator														
Regions	**1.5°C GWL**	**Std**		**2°C GWL**	**Std**		**2.7°C GWL**	**Std**		**3.2°C GWL**	**Std**		**4.5°C GWL**	**Std**
WCE	0.59	0.14		0.50	0.15		0.39	0.15		0.35	0.14		0.26	0.11
NEU	0.84	0.18		0.78	0.23		0.65	0.29		0.59	0.31		0.43	0.33
SEU	0.75	0.13		0.69	0.14		0.57	0.16		0.52	0.16		0.38	0.15
EEU	0.69	0.21		0.60	0.23		0.43	0.25		0.36	0.24		0.19	0.19
Amphibians														
Regions	**1.5°C GWL**	**Std**		**2°C GWL**	**Std**		**2.7°C GWL**	**Std**		**3.2°C GWL**	**Std**		**4.5°C GWL**	**Std**
WCE	0.88	0.12		0.84	0.14		0.76	0.17		0.72	0.17		0.59	0.18
NEU	0.89	0.24		0.91	0.16		0.87	0.19		0.84	0.21		0.76	0.25
SEU	0.84	0.16		0.79	0.18		0.68	0.21		0.63	0.22		0.50	0.22
EEU	0.83	0.29		0.86	0.20		0.78	0.24		0.75	0.25		0.63	0.30
Reptiles														
Regions	**1.5°C GWL**	**Std**		**2°C GWL**	**Std**		**2.7°C GWL**	**Std**		**3.2°C GWL**	**Std**		**4.5°C GWL**	**Std**
WCE	0.89	0.09		0.86	0.10		0.80	0.11		0.77	0.11		0.67	0.13
NEU	0.90	0.18		0.87	0.19		0.82	0.22		0.79	0.23		0.71	0.25
SEU	0.89	0.10		0.85	0.12		0.76	0.15		0.72	0.15		0.58	0.15
EEU	0.87	0.27		0.84	0.28		0.79	0.30		0.78	0.31		0.68	0.33
Birds														
Regions	**1.5°C GWL**	**Std**		**2°C GWL**	**Std**		**2.7°C GWL**	**Std**		**3.2°C GWL**	**Std**		**4.5°C GWL**	**Std**
WCE	0.88	0.04		0.85	0.05		0.79	0.06		0.76	0.07		0.66	0.11
NEU	0.93	0.13		0.92	0.12		0.90	0.12		0.88	0.13		0.83	0.16
SEU	0.87	0.06		0.82	0.08		0.73	0.10		0.69	0.11		0.54	0.12
EEU	0.86	0.14		0.84	0.15		0.79	0.16		0.77	0.16		0.69	0.18

Mammals															
Regions	1.5°C GWL	Std		2°C GWL	Std		2.7°C GWL	Std		3.2°C GWL	Std		4.5°C GWL	Std
WCE	0.79	0.10		0.73	0.11		0.61	0.12		0.55	0.12		0.42	0.12
NEU	0.90	0.11		0.87	0.12		0.81	0.16		0.77	0.17		0.63	0.23
SEU	0.78	0.12		0.70	0.14		0.59	0.16		0.54	0.16		0.38	0.15
EEU	0.80	0.16		0.75	0.19		0.65	0.20		0.60	0.19		0.44	0.16

Notes:

WCE: Western Central Europe, NEU: Northern Europe, SEU: Southern Europe, EEU: Eastern Europe.

Species are projected to remain within their suitable climate conditions at increasing levels of climate change averaged over 21 CMIP5 climate models with standard deviation (Std) (Warren et al., 2018). There is increased loss of climatic niche with warming increasing from 1.5°C to 4.5°C GWL. Risks that appear to be lower in some groups through droughts, habitat fragmentation and loss are not considered and will exacerbate the risks, while dispersal may reduce risk.

SM13.3 Supplementary Material Supporting Section 13.4

Table SM13.4 | Literature sources used for assessment of impacts on and risks for marine and coastal ecosystems (Figure 13.11)

Impact/risk	Supporting references of assessment
Loss of habitat availability	Coma et al. (2009); Garrabou et al. (2009); Huete-Stauffer et al. (2011); Munari (2011); Kersting et al. (2013); Brodie et al. (2014); Frolov et al. (2014); Rivetti et al. (2014); Altieri and Gedan (2015); García Molinos et al. (2016); Spencer et al. (2016); Bakanev (2017); Jessen et al. (2017); Orekhova (2017); Berlinski and Popov (2018); Buonomo et al. (2018); Jokinen et al. (2018); Reusch et al. (2018); Schuerch et al. (2018); van der Spek (2018); Wang et al. (2018); Filatov et al. (2019); Garrabou et al. (2019); Saraiva et al. (2019); Spivak et al. (2019); D'Amen and Azzurro (2020); Jiang et al. (2020); Pavlova (2020); Sandø et al. (2020); Stepanyan (2020)
Shifts in ranges (including invasions), composition (taxonomic, functional), phenologies	Kortsch et al. (2015); Assis et al. (2017); Bakanev (2017); Frainer et al. (2017); Kotenev et al. (2017); Rasmussen et al. (2017); Raybaud et al. (2017); Townhill et al. (2017); Vasilakopoulos et al. (2017); Benedetti et al. (2018); Gaudin et al. (2018); Jonsson et al. (2018); Kotta et al. (2018); Minicheva et al. (2018); Townhill et al. (2018); Benedetti et al. (2019); Berdnikov et al. (2019); Casado-Amezúa et al. (2019); Chefaoui et al. (2019); de la Hoz et al. (2019); Erauskin-Extramiana et al. (2019); Filatov et al. (2019); Hjerne et al. (2019); Kröncke et al. (2019); Krovnin et al. (2019); Moullec et al. (2019); Wasmund et al. (2019); Baudron et al. (2020); Bedford et al. (2020); Clark et al. (2020); Desmit et al. (2020); Maltby et al. (2020); Martynova et al. (2020); Nohe et al. (2020); Pavlova (2020); Pecuchet et al. (2020); Pennino et al. (2020); Pyatinsky et al. (2020); Stepanyan (2020); Uriarte et al. (2021)
Reduction in growth and reproductive success	Bramanti et al. (2013); Maier et al. (2013); Gazeau et al. (2014); Hennige et al. (2015); Wall et al. (2015); Ragazzola et al. (2016); Stiasny et al. (2016); Durant and Hjermann (2017); Smoliński and Mirny (2017); Thomsen et al. (2017); Capuzzo et al. (2018); Lindegren et al. (2018); Queirós et al. (2018); Sswat et al. (2018a); Sswat et al. (2018b); Stiasny et al. (2018); Coll et al. (2019); Franz et al. (2019); Goldberg et al. (2019); Herrera et al. (2019); Hidalgo et al. (2019); Sguotti et al. (2019a); Stiasny et al. (2019); Tanner et al. (2019); Tsikliras et al. (2019); Verezemskaya et al. (2019); Vieira et al. (2019); Voss et al. (2019); Denechaud et al. (2020); Maynou et al. (2020); Mitchell et al. (2020); Tanner et al. (2020); Ikpewe et al. (2021); Polte et al. (2021)
Loss of biodiversity	Berlinski and Popov (2018); IPBES (2018); Filatov et al. (2019); Pyatinsky et al. (2020); Stepanyan (2020)
Decline in production	Maugendre et al. (2014); Arrigo and van Dijken (2015); Laufkotter et al. (2015); Holt et al. (2016); Børsheim (2017); Orekhova (2017); Capuzzo et al. (2018); Holt et al. (2018); Minicheva et al. (2018); Berdnikov et al. (2019); Bryndum-Buchholz et al. (2019); Carozza et al. (2019); Free et al. (2019); Kwiatkowski et al. (2019); Lotze et al. (2019b); Verezemskaya et al. (2019); Lewis et al. (2020); Pyatinsky et al. (2020)
Emergence of harmful algal blooms and pathogens	Frolov et al. (2014); Baker-Austin et al. (2017); Semenza et al. (2017); Minicheva et al. (2018); Riebesell et al. (2018); Roggatz et al. (2019)
Reduction in ecosystem services	Roebeling et al. (2013); Brodie et al. (2014); Carstensen et al. (2014); Kjesbu et al. (2014); Maugendre et al. (2014); Serra et al. (2015); Krumhansl et al. (2016); De los Santos et al. (2017); Gao et al. (2018); van der Spek (2018); Wang et al. (2018); Moullec et al. (2019); Sguotti et al. (2019b); Sheverdyaev (2019); Baudron et al. (2020); Maltby et al. (2020)

SM13.4 Supplementary Material Supporting Section 13.5

Table SM13.5 | Literature sources used in the assessment of feasibility and effectiveness of adaptation options for food systems in Europe (Figure 13.14)

		Effectiveness	Feasibility					
Impact type	**Adaptation option**		**Economic**	**Technological**	**Institutional**	**Sociocultural**	**Ecological**	**Geophysical**
Heat stress	Irrigation	Dono et al. (2013); Schaap et al. (2013); Sutton et al. (2013); Bird et al. (2016); Diogo et al. (2017); Siebert et al. (2017); Webber et al. (2018); Feyen et al. (2020); Holzkämper, 2020); Santillán et al. (2020); Kebede et al. (2021)	Dono et al. (2013); Schaap et al. (2013); Sutton et al. (2013); Bird et al. (2016); Costa et al. (2016); Diogo et al. (2017); Holzkämper (2020); Kebede et al. (2021)	Dono et al. (2013); Schaap et al. (2013); Sutton et al. (2013); Bird et al. (2016); Costa et al. (2016); Diogo et al. (2017); Siebert et al. (2017); Neset et al. (2019); Holzkämper (2020); Santillán et al. (2020); Kebede et al. (2021)	Schaap et al. (2013); Mandryk et al. (2015); Bird et al. (2016); Kebede et al. (2021)	Schaap et al. (2013); Sutton et al. (2013); Mandryk et al. (2015); Costa et al. (2016); Neset et al. (2019); Kebede et al. (2021)	Dono et al. (2013); Sutton et al. (2013); Bird et al. (2016); Costa et al. (2016); Siebert et al. (2017); Webber et al. (2018); Neset et al. (2019); Holzkämper (2020); Santillán et al. (2020); Kebede et al. (2021)	Dono et al. (2013); Webber et al. (2018); Neset et al. (2019); Kebede et al. (2021)
	Change of sowing/ harvest date	Schaap et al. (2013); Trnka et al. (2014); Donatelli et al. (2015); Gabaldon-Leal et al. (2015); Peltonen-Sainio et al. (2016); Diogo et al. (2017); Feyen et al. (2020); Holzkämper (2020)	Schaap et al. (2013); Trnka et al. (2014); Donatelli et al. (2015); Diogo et al. (2017); Grüneis et al. (2018)	Trnka et al. (2014); Donatelli et al. (2015); Gabaldon-Leal et al. (2015); Feyen et al. (2020); Holzkämper (2020)		Schaap et al. (2013); Donatelli et al. (2015); Mandryk et al. (2015); Peltonen-Sainio et al. (2016); Diogo et al. (2017); Grüneis et al. (2018)	Donatelli et al. (2015); Peltonen-Sainio et al. (2016); Holzkämper (2020)	Schaap et al. (2013); Diogo et al. (2017); Holzkämper (2020)
	Change of cultivars	Sutton et al. (2013); Trnka et al. (2014); Gabaldon-Leal et al. (2015); Costa et al. (2016); Peltonen-Sainio et al. (2016); Rial-Lovera et al. (2017); Webber et al. (2018); Santillán et al. (2020)	Sutton et al. (2013); Trnka et al. (2014); Rial-Lovera et al. (2017); Grüneis et al. (2018); Holzkämper (2020)	Sutton et al. (2013); Trnka et al. (2014); Gabaldon-Leal et al. (2015); Costa et al. (2016); Rial-Lovera et al. (2017); Webber et al. (2018); Feyen et al. (2020); Holzkämper (2020); Santillán et al. (2020)		Sutton et al. (2013); Costa et al. (2016); Peltonen-Sainio et al. (2016); Grüneis et al. (2018)	Sutton et al. (2013); Rial-Lovera et al. (2017); Holzkämper (2020); Santillán et al. (2020)	Rial-Lovera et al. (2017); Webber et al. (2018); Santillán et al. (2020)
	Livestock management	Vitali et al. (2015); Cox et al. (2016); Schauberger et al. (2020)	Vitali et al. (2015); Schauberger et al. (2020)	Morignat et al. (2014); Vitali et al. (2015); Cox et al. (2016); Schauberger et al. (2020)		Vitali et al. (2015); Cox et al. (2016)	Morignat et al. (2014); Vitali et al. (2015); Cox et al. (2016)	

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Drought	Irrigation	Dono et al. (2013); Schaap et al. (2013); Sutton et al. (2013); Bird et al. (2016); Diogo et al. (2017); Stańczuk-Gałwiaczek et al. (2018); Webber et al. (2018); Harmanny and Malek (2019); Holzkämper (2020); Santillán et al. (2020)	Dono et al. (2013); Schaap et al. (2013); Sutton et al. (2013); Costa et al. (2016); Diogo et al. (2017); Harmanny and Malek (2019); Holzkämper (2020); Kebede et al. (2021)	Dono et al. (2013); Schaap et al. (2013); Sutton et al. (2013); Mandryk et al. (2015); van Duinen et al. (2015); Bird et al. (2016); Costa et al. (2016); Diogo et al. (2017); Stańczuk-Gałwiaczek et al. (2018); Harmanny and Malek (2019); Feyen et al. (2020); Holzkämper (2020); Santillán et al. (2020); Kebede et al. (2021)	Schaap et al. (2013); Mandryk et al. (2015); Bird et al. (2016); Grüneis et al. (2018); Kebede et al. (2021)	Schaap et al. (2013); Sutton et al. (2013); Mandryk et al. (2015); van Duinen et al. (2015); Costa et al. (2016); Grüneis et al. (2018); Stańczuk-Gałwiaczek et al. (2018); Harmanny and Malek (2019); Kebede et al. (2021)	Dono et al. (2013); Sutton et al. (2013); Bird et al. (2016); Costa et al. (2016); Stańczuk-Gałwiaczek et al. (2018); Webber et al. (2018); Harmanny and Malek (2019); Holzkämper (2020); Santillán et al. (2020); Kebede et al. (2021)	Dono et al. (2013); Diogo et al. (2017); Harmanny and Malek (2019); Santillán et al. (2020); Kebede et al. (2021)
	Change of sowing/ harvest date	Schaap et al. (2013); Trnka et al. (2014); Donatelli et al. (2015); Gabaldon-Leal et al. (2015); Peltonen-Sainio et al. (2016); Diogo et al. (2017); Parent et al. (2018); Lamichhane et al. (2019); Feyen et al. (2020); Holzkämper (2020)	Schaap et al. (2013); Trnka et al. (2014); Donatelli et al. (2015); Diogo et al. (2017); Grüneis et al. (2018); Lamichhane et al. (2019)	Trnka et al. (2014); Donatelli et al. (2015); Gabaldon-Leal et al. (2015); Feyen et al. (2020); Holzkämper (2020)		Schaap et al. (2013); Donatelli et al. (2015); Mandryk et al. (2015); Peltonen-Sainio et al. (2016); Diogo et al. (2017); Grüneis et al. (2018)	Donatelli et al. (2015); Peltonen-Sainio et al. (2016); Holzkämper (2020)	Schaap et al. (2013); Diogo et al. (2017); Holzkämper (2020)
	Change of cultivars	Sutton et al. (2013); Trnka et al. (2014); Gabaldon-Leal et al. (2015); Costa et al. (2016); Peltonen-Sainio et al. (2016); Rial-Lovera et al. (2017); Parent et al. (2018); Webber et al. (2018); Santillán et al. (2020)	Sutton et al. (2013); Trnka et al. (2014); Rial-Lovera et al. (2017); Grüneis et al. (2018); Holzkämper (2020)	Sutton et al. (2013); Trnka et al. (2014); Gabaldon-Leal et al. (2015); Costa et al. (2016); Rial-Lovera et al. (2017); Webber et al. (2018); Feyen et al. (2020); Holzkämper (2020); Santillán et al. (2020)		Sutton et al. (2013); Costa et al. (2016); Peltonen-Sainio et al. (2016); Grüneis et al. (2018)	Sutton et al. (2013); Rial-Lovera et al. (2017); Holzkämper (2020); Santillán et al. (2020)	Rial-Lovera et al. (2017); Webber et al. (2018); Santillán et al. (2020)
	Soil management	Schönhart et al. (2014); Rial-Lovera et al. (2017); Hamidov et al. (2018); Wiréhn (2018); Jørgensen et al. (2020); Wiréhn et al. (2020)	Schönhart et al. (2014); Rial-Lovera et al. (2017); Hamidov et al. (2018); Wiréhn (2018); EEA (2019b); Wiréhn et al. (2020)	Schönhart et al. (2014); Rial-Lovera et al. (2017); Hamidov et al. (2018); Wiréhn (2018); Wiréhn et al. (2020)	Rial-Lovera et al. (2017); Wiréhn (2018); Jørgensen et al. (2020)	Rial-Lovera et al. (2017); Wiréhn (2018)	Rial-Lovera et al. (2017); Hamidov et al. (2018); Wiréhn (2018)	Rial-Lovera et al. (2017); Hamidov et al. (2018); Wiréhn (2018)
Flooding	Change of sowing/ harvest date	Sutton et al. (2013); Rial-Lovera et al. (2017); Stańczuk-Gałwiaczek et al. (2018); Neset et al. (2019)	Rial-Lovera et al. (2017); Neset et al. (2019); Kebede et al. (2021)	Sutton et al. (2013); Papadaskalopoulou et al. (2016); Rial-Lovera et al. (2017); Stańczuk-Gałwiaczek et al. (2018); Neset et al. (2019)			Sutton et al. (2013); Stańczuk-Gałwiaczek et al. (2018); Neset et al. (2019); Kebede et al. (2021)	Sutton et al. (2013); Stańczuk-Gałwiaczek et al. (2018); Neset et al. (2019); Kebede et al. (2021)

		Effectiveness	Feasibility					
Impact type	**Adaptation option**		**Economic**	**Technological**	**Institutional**	**Sociocultural**	**Ecological**	**Geophysical**
Compound and extreme weather	Plant and livestock breeding	Trnka et al. (2014); Macholdt and Honermeier (2017); Rial-Lovera et al. (2017); Costa et al. (2019a); Senapati et al. (2019); Wreford and Topp (2020)	Trnka et al. (2014); Macholdt and Honermeier (2017); Rial-Lovera et al. (2017); Costa et al. (2019a); Senapati et al. (2019); Wreford and Topp (2020)	Rial-Lovera et al. (2017); Costa et al. (2019a); Senapati et al. (2019); Wreford and Topp (2020)			Wiréhn (2018); Costa et al. (2019a); Holzkämper (2020); Wreford and Topp (2020)	Rial-Lovera et al. (2017); Wreford and Topp (2020)
	Mixed use: agroecology and agroforestry	Lüscher et al. (2014); Moraine et al. (2014); Himanen et al. (2016); Hernández-Morcillo et al. (2018)	Lüscher et al. (2014); Moraine et al. (2014); Himanen et al. (2016); Rojas-Downing et al. (2017); Hernández-Morcillo et al. (2018)	Moraine et al. (2014); Hernández-Morcillo et al. (2018)	Moraine et al. (2014); Hernández-Morcillo et al. (2018)	Moraine et al. (2014); Hernández-Morcillo et al. (2018)	Moraine et al. (2014); Hernández-Morcillo et al. (2018); Öllerer et al. (2019); Oggioni et al. (2020)	Prem et al. (2014); Fornara et al. (2019); Oggioni et al. (2020); Ford et al. (2021)
	Agricultural policy changes	Papadaskalopoulou et al. (2016); Erjavec et al. (2017); McVittie et al. (2018); Muenzel and Martino (2018); Faria and Morales (2020)	Buelow and Cradock-Henry (2018); Grüneis et al. (2018); McVittie et al. (2018); Muenzel and Martino (2018); Sneessens et al. (2019); Faria and Morales (2020)	Li et al. (2017); Wiréhn (2018); EEA (2019b); Szumelda (2019)	Reidsma et al. (2015); Papadaskalopoulou et al. (2016); Li et al. (2017); Grüneis et al. (2018); McVittie et al. (2018); Muenzel and Martino (2018); Wiréhn (2018); Sneessens et al. (2019); Szumelda (2019); Faria and Morales (2020); Jørgensen et al. (2020); Mitter et al. (2020)	Li et al. (2017); Buelow and Cradock-Henry (2018); Nguyen et al. (2019); Sneessens et al. (2019); Szumelda (2019)	McVittie et al. (2018); Muenzel and Martino (2018); Faria and Morales (2020)	McVittie et al. (2018); Muenzel and Martino (2018); Faria and Morales (2020)
	Training and information	Li et al. (2017); Rial-Lovera et al. (2017); Buelow and Cradock-Henry (2018); Nguyen et al. (2019)	Rial-Lovera et al. (2017); McVittie et al. (2018); Szumelda (2019)		Li et al. (2017); Rial-Lovera et al. (2017); McVittie et al. (2018)	Nguyen et al. (2019); Szumelda (2019)	Li et al. (2017); Rial-Lovera et al. (2017); McVittie et al. (2018)	Li et al. (2017); Rial-Lovera et al. (2017); McVittie et al. (2018)
	Crop selection changes	Lüscher et al. (2014); Trnka et al. (2015); Rial-Lovera et al. (2017); Li et al. (2018); Harmanny and Malek (2019)	Lüscher et al. (2014); Reidsma et al. (2015); Wiréhn (2018); Wiréhn et al. (2020)	Lüscher et al. (2014); Trnka et al. (2015); Rial-Lovera et al. (2017); Li et al. (2018); Wiréhn et al. (2020)		Himanen et al. (2016); Ricart et al. (2019)	Rial-Lovera et al. (2017); Li et al. (2018); Harmanny and Malek (2019); Wiréhn et al. (2020)	Rial-Lovera et al. (2017); Li et al. (2018); Harmanny and Malek (2019); Wiréhn et al. (2020)
	Land cover change (including agricultural land abandonment)	Leclère et al. (2013); Dunford et al. (2015); Kebede et al. (2021)	Dunford et al. (2015); Alexander et al. (2018); Kebede et al. (2021)	Leclère et al. (2013); Mandryk et al. (2015); Alexander et al. (2018)	Mandryk et al. (2015)	Leclère et al. (2013); Mandryk et al. (2015); Neset et al. (2019)	Dunford et al. (2015); Rabin et al. (2020); Kebede et al. (2021)	Dunford et al. (2015); Rabin et al. (2020); Kebede et al. (2021)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Disease pathogens and vectors	Plant and livestock breeding	Hoffmann (2013)	Hoffmann (2013)	Hoffmann (2013)	Hoffmann (2013); Grüneis et al. (2018)	Hoffmann (2013); Neset et al. (2019)		
	Management (including high-frequency rotations)	Maclachlan and Guthrie (2010); Skuce et al. (2013); Moraine et al. (2014)	Maclachlan and Guthrie (2010); Morgan and van Dijk (2012); Wiréhn et al. (2020)	Dórea et al. (2016); Harrus and Baneth (2005); Moraine et al. (2014); Pascual-Linaza et al. (2014); Skuce et al. (2013)	Harrus and Baneth (2005); Moraine et al. (2014); Roberts et al. (2014); Dórea et al. (2016)	Morgan and van Dijk (2012); Wiréhn et al. (2020)	Acevedo et al. (2010); Maclachlan and Guthrie (2010); Martínez-López et al. (2014); Moraine et al. (2014); Rose Vineer et al. (2020)	Maclachlan and Guthrie (2010); Moraine et al. (2014); Paz (2015); Tjaden et al. (2018); Rose Vineer et al. (2020)
Combined impacts on productivity	International trade changes	Dunford et al. (2015); Holman et al. (2016); Alexander et al. (2018); EEA (2019b)				Dunford et al. (2015); Holman et al. (2016); Mitter et al. (2020); Kebede et al. (2021)	Dunford et al. (2015); Holman et al. (2016); Kebede et al. (2021)	Alexander et al. (2018); EEA (2019b)
	Consumer shifts in consumption		Dunford et al. (2015); Mitter et al. (2020)			Dunford et al. (2015); Mitter et al. (2020)		

SM13.5 Supplementary Material Supporting Section 13.6

Table SM13.6 | Sign of future change in onshore wind power potential under global warming levels (Figure 13.16)

Sub-region	Area in study	Onshore wind power potential (sign of change)					
		1.5˚C		2˚C		≥3˚C	
Northern Europe							
Davy et al. (2018)	Europe, North Africa, Middle East	–		–	No model agreement over large areas	–	No model agreement over large areas
Moemken et al. (2018)	Europe	–		+/–	+ only over a minor part of Scandinavia W: + in central Scandinavia, – in the rest S: – except northern Norway	+/–	+ over northern Scandinavia W: + in almost all areas S: –
Devis et al. (2018)	Europe	+	W: + S: + except in the Baltic				
Tobin et al. (2018a)	EU and Switzerland	–	Some ensemble members project increases up to 5%	–	Some ensemble members project increases up to 4%	–	Some ensemble members project increases up to 4%
Reyers et al. (2016)	Europe (without Russia)			+	W: +, S: –	+	W: +, S: –
Carvalho et al. (2017b)	Europe (without Russia)	–	– in southern UK and northern Norway, rest: n. s. W: few –, rest: n. s. S: few –, most of Scandinavia: n. s.	+/–	+ in southern Finland, in southern Norway: n. s. W: few –, rest: n. s. S: +/–, most of Scandinavia: n. s.	+/–	+ in southern Finland, in southern Norway: n. s. W: few –, rest: n. s. S: +/–, most of Scandinavia: n. s.
Tobin et al. (2016)	Europe	–		–			
Després and Adamovic (2020)	EU	n.c.		n.c.		–	

Sub-region	Area in study	Onshore wind power potential (sign of change)					
		1.5˚C		2˚C		≥3˚C	
Western Central Europe							
Reyers et al. (2016)	Europe (without Russia)			n.c./+/–	n.c. over half of France, – in the rest of France	n.c./+/–	n.c. over half of France, – in the rest of France
Moemken et al. (2018)	Europe	–		–	W: +/– (and opposite signs of change between RCMs over large areas) S: +/–	+/–	+ over coastal Poland W: +/– (and opposite signs of change between RCMs over most areas) S: +/– (but – in most areas)
Davy et al. (2018)	Europe, North Africa, Middle East	–	No model agreement over France, Belarus, Ukraine	–	No model agreement over Poland, Belarus	+/–	No model agreement over large areas; parts of Ukraine and Belarus with +
Carvalho et al. (2017b)	Europe (without Russia)	–	Changes n. s. over large areas W: –, S: –	–	Changes n. s. over large areas W: –, S: –	–	Changes n. s. over large areas W: –, S: –
Devis et al. (2018)	Europe	+/–	– in Belarus, Ukraine and most of France W: +/–, S: +/–				
Tobin et al. (2018a)	EU and Switzerland	–		–		–	
Tobin et al. (2016)	Europe	+/–	– for Poland	+			
Després and Adamovic (2020)	EU	n.c.		n.c.		+	
Southern Europe							
Solaun and Cerdá (2020)	Spain	+/–		+/–			
Katopodis et al. (2019)	Greece	+/–		+/–			
Reyers et al. (2016)	Europe			+/–	+ only over a few areas in Turkey and Greece; high robustness in – sign W: –, S: +/–	–	High robustness in sign W: –, S: +/–
Moemken et al. (2018)	Europe	+/–	+ in Turkey, large parts of Italy and Greece, and southern France	+/–	+ in Turkey W: – except southern France and central Italy S: + in Turkey and most of Spain, – in the rest	+/–	+ in coastal Turkey W: – except Croatia, central Italy and southern France where models disagree S: +/–
Davy et al. (2018)	Europe, North Africa, Middle East	+/–	+ over coastal Turkey and a few more locations	+/–	+ over coastal Turkey and a few more locations	+/–	+ over a small part of coastal Turkey
Devis et al. (2018)	Europe	–	W: –, S: + in southern Iberia, in the rest – in the day and + in the night				

Sub-region	Area in study	Onshore wind power potential (sign of change)					
		1.5°C		2°C		≥3°C	
Carvalho et al. (2017b)	Europe	–	In Turkey, changes n. s. W: few –, rest: n. s. S: +/–, most: n. s.	–	In Turkey, changes n. s. W: few –, rest: n. s. S: +/–, most: n. s.	+/–	+ over northern Turkey W: –, Turkey mostly n. s. S: +/– (+ in Turkey and northern Iberia)
Tobin et al. (2018a)	EU and Switzerland	+/–	+ only for Greece	+/–	+ only for Greece	+/–	+ only for Greece
Tobin et al. (2016)	Europe	–		–			
Després and Adamovic (2020)	EU	n.c.		n.c.		+	
Eastern Europe							
Devis et al. (2018)		+	W: +, S: +/–				
Carvalho et al. (2017b)		–	W: –, S: –	–	W: –, S: –	–	W: –, S: –
Davy et al. (2018)	Europe, North Africa, Middle East	–		–	No model agreement over a large part of the sub-region	–	No model agreement over most of the sub-region
Moemken et al. (2018)		–		–	W: – over southwest Russia, disagreement between RCMs on northwest Russia S: –	–	W: – no model agreement between RCMs on sign S: –

Notes:

+: increase, –: decrease, +/–: increase in some regions and decrease in others, n. s.: not statistically significant, n.c.: no change, W: winter, S: summer

For those studies not reporting a global warming level but only an RCP scenario–timeline combination, the latter was associated with the relevant global mean temperature increase.

Table SM13.7 | Magnitude of future change in onshore wind power potential under global warming levels (Figure 13.16)

	Onshore wind power potential (magnitude of change)			
Sub-region	1.5°C	2°C	≥3°C	Measurement unit in study
Northern Europe				
Davy et al. (2018)	–3 to 0%	–8 to 0%	–10 to 0%	Wind power density
Moemken et al. (2018)	–2 to 0%	–8 to 4% (W: –6 to 6%, S: –12 to 6%)	–8 to 6% (W: –4 to 14%, S: –20 to –4%)	Wind energy output
Devis et al. (2018)	4 to 8% (W: up to 7%, S: –7 to 6%)			Mean power output
Tobin et al. (2018a)	–2to 0%	–2 to –1%	–6 to –2.5%	Wind power production
Reyers et al. (2016)		0 to 1% (W: 0 to 3%, S: –3 to 0%)	1 to 4% (W: 0 to 8%, S: –7 to 0%)	Wind energy output
Carvalho et al. (2017b)	–15 to 0% (W: –15 to –5%, S: –15 to –5%)	–20 to 20% (W: –15 to –5%, S: –15 to 20%)	–20 to 30% (W: –15 to 0%, S: –30 to 15%)	Wind energy density
Tobin et al. (2016)	–2 to –1%	–3 to –1%		Annual energy yield
Després and Adamovic (2020)	0%	0%	–5 to –1%	Electricity production from wind
Western Central Europe				
Reyers et al. (2016)		–1 to 1%	–1 to 2%	Wind energy output
Moemken et al. (2018)	–2 to 0%	–4 to 0% (W: –4 to 12%, S: –14 to 0%)	–6 to 4% (W: –4 to 18%, S: –18 to 4%)	Wind energy output
Davy et al. (2018)	–3 to 0%	–3 to 0%	–5 to 2%	Wind power density
Carvalho et al. (2017b)	–30 to 0% (W: –40 to –5%, S: –30 to –5%)	–12 to 0% (W: –40 to –5%, S: –30 to –5%)	–12 to 0% (W: –40 to –5%, S: –30 to –5%)	Wind energy density

	Onshore wind power potential (magnitude of change)			
Sub-region	**1.5˚C**	**2˚C**	**≥3˚C**	**Measurement unit in study**
Devis et al. (2018)	–3 to 5% (W: –5 to 5%, S: –8 to –5%)			Mean power output
Tobin et al. (2018a)	–2.5 to 0%	–4 to –1%	–4 to –1%	Wind power production
Tobin et al. (2016)	–0.5 to 1%	–3 to 2%		Annual energy yield
Després and Adamovic (2020)	0%	0%	0 to 2%	Electricity production from wind
Southern Europe				
Solaun and Cerdá (2020)	–8.2 to 5%	–8 to 6.5%		Production
Katopodis et al. (2019)	–15 to 8%	–5 to 8%		Wind potential
Reyers et al. (2016)		–2 to 0.8% (W: –2 to 0%, S: –6 to 1%)	–4 to 0% (W: –7 to –2%, S: –8 to 2%)	Wind energy output
Moemken et al. (2018)	–4 to 4%	–6 to 4% (W: –6 to 4%, S: –8 to 16%)	–14 to 12% (W: –16 to 16%, S: –12 to 18%)	Wind energy output
Davy et al. (2018)	–5 to 7%	–8 to 6%	–17 to 15%	Wind power density
Devis et al. (2018)	–12 to –2% (W: –12 to –6%, S: –8 to 6%)			Mean power output
Carvalho et al. (2017b)	–10 to –5% (W: –15 to –5%, S: –10 to –5%)	–10 to –5% (W: –15 to –5%, S: –20 to 20%)	–15 to 5% (W: –15 to –5%, S: –30 to 30%)	Wind energy density
Tobin et al. (2018a)	–4 to 1%	–4 to 1%	–8 to 3%	Wind power production
Tobin et al. (2016)	–2 to –1%	–6 to –4%		Annual energy yield
Després and Adamovic (2020)	0%	0%	0 to 2%	Electricity production from wind
Eastern Europe				
Devis et al. (2018)	–10 to 0% (W: –8 to 2%, S: –10 to 2%)			Mean power output
Carvalho et al. (2017b)	–30 to –5% (W: –20 to –10%, S: –30 to –5%)	–10 to 0% (W: –20 to –5%, S: –10 to –5%)	–20 to –5% (W: –20 to –5%, S: –20 to –5%)	Wind energy density
Davy et al. (2018)	–5 to –3%	–8 to –3%	–15 to –5%	Wind power density
Moemken et al. (2018)	–2 to 0%	–2 to 0% (W: –4 to 6%, S: –6 to 0%)	–4 to 0% (W: –4 to 8%, S: –12 to –4%)	Wind energy output

Notes:

In many studies, changes are provided in map format and thus figures in this table are our own interpretation of these map-based findings. Ranges illustrate variations within sub-regions. Values correspond to ensemble means, unless characterised otherwise.

Table SM13.8 | Sign of future change in offshore wind power potential under global warming levels (Figure 13.16)

Sub-region	Area in study	Offshore wind power potential (sign of change)					
		1.5˚C		2˚C		≥3˚C	
Northern Europe							
Davy et al. (2018)	Europe, North Africa, Middle East	+/–	+ in a few parts of Baltic Sea, – in upper North Sea	+/–	+ in most of Baltic Sea, – in lower North Sea	+/–	+ in Baltic Sea, – in North Sea
Moemken et al. (2018)	Europe	+/–	+ in Baltic Sea, +/– in North Sea	+/–	+ in Baltic Sea, – in North Sea W: + S: + in Baltic Sea, – in North Sea	+/–	+ in Baltic Sea, – in North Sea W: +/– S: + in Baltic Sea, – in North Sea
Reyers et al. (2016)	Europe			+/–	+/– in Baltic Sea, +/– in the rest W: +, S: –	+/–	+/– in Baltic Sea, +/– in the rest W: +, S: –
Devis et al. (2018)	Europe	+	W: +, S: +				
Southern Europe							
Katopodis et al. (2019)	Greece	+/–	– in Ionian Sea and most of Aegean Sea	+/–	– in Ionian Sea and most of Aegean Sea		

Sub-region	Area in study	Offshore wind power potential (sign of change)					
		1.5˚C		2˚C		≥3˚C	
Reyers et al. (2016)	Europe			+/–	+/– in Aegean Sea, – in the rest W: n.a. S: n.a.	–	– in almost all of Aegean Sea and in the rest W: n.a. S: n.a.
Koletsis et al. (2016)	Mediterranean and Black seas	+/–	+ in Aegean Sea, – in the rest			+/–	+ in Aegean Sea, – in the rest
Moemken et al. (2018)	Europe	+/–	+ in Aegean and Adriatic seas, – in the rest	+/–	+ in Aegean and Adriatic seas, – in the rest W: +/– S: + in Aegean and Adriatic seas, – in the rest	+/–	+ in most of Aegean Sea, – in the rest W: – S: + in Aegean and Adriatic seas, – in the rest
Devis et al. (2018)	Europe	–	– in most of Mediterranean Sea, n.c. in Aegean Sea W: – S: + in most of Aegean Sea, +/– in the rest				
Davy et al. (2018)	Europe, North Africa, Middle East	+/–	+ in most of Aegean Sea, – in the rest	+/–	+ in most of Aegean Sea, – in the rest	+/–	+ in most of Aegean Sea, – in the rest
Alvarez and Lorenzo (2019)	EU	+/–	+ in most of Aegean Sea, +/– in the rest	+/–	+ in most of Aegean Sea, – in most of the rest		

Notes:

+: increase, –: decrease, +/–: increase in some regions and decrease in others, n.c.: no change, W: winter, S: summer, n.a.: not available

For those studies not reporting a global warming level but only an RCP scenario–timeline combination, the latter was associated with the relevant global mean temperature increase.

Table SM13.9 | Magnitude of future change in offshore wind power potential under global warming levels (Figure 13.16)

	Offshore wind power potential (magnitude of change)			
Sub-region	1.5˚C	2˚C	≥3˚C	Measurement unit in study
Northern Europe				
Davy et al. (2018)	–3 to 3%	–1 to 5%	–10 to 7%	Wind power density
Moemken et al. (2018)	–2 to 4%	–2 to 4% (W: –2 to 4%, S: 4 to 8%)	–4 to 4% (W: –4 to 4%, S: –8 to 6%)	Wind energy output
Reyers et al. (2016)		–1 to 0.5% (W: 0 to 2%, S: –2 to 0%)	–1 to 1% (W: 0 to 2%, S: –2 to 0%)	Wind energy output
Devis et al. (2018)	0 to 3% (W: 0 to 3%, S: 0 to 3%)			Mean power output
Southern Europe				
Katopodis et al. (2019)	–15 to 5%	–15 to 5%		Wind potential
Reyers et al. (2016)		–1 to 1% (W: 0 to 2%, S: –2 to 0%)	–1 to 1% (W: 0 to 2%, S: –2 to 0%)	Wind energy output
Moemken et al. (2018)	–2 to 4%	–4 to 2% (W: 0 to 4%, S: –4 to 8%)	–8 to 4% (W: –4 to 4%, S: –8 to 8%)	Wind energy output
Koletsis et al. (2016)	>5%		< –5% to >5%	Wind power
Devis et al. (2018)	–4 to 0%			Mean power output
Davy et al. (2018)	–6 to 6%	–10 to 6%	–15 to 12%	Wind power density

Notes:

In many studies, changes are provided in map format and thus figures in this table are our own interpretation of these map-based findings. Ranges illustrate variations within sub-regions. Values correspond to ensemble means, unless characterised otherwise.

Table SM13.10 | Sign and magnitude of future change in solar power potential under global warming levels (Figure 13.16)

Sub-region	Area in study	Solar power potential (magnitude of change)								
		1.5°C			2°C			≥3°C		
Northern Europe										
Tobin et al. (2018a)	EU and Switzerland	–		–4 to –1%	–		–6 to –2%	–		–8 to –3%
Jerez et al. (2015)	Europe				–	Higher decrease in northern Scandinavia	–10 to 0%	–	Higher decrease in northern Scandinavia	–20 to 0%
Gutiérrez et al. (2020)	Europe				+/–	– in southern Norway and northern UK in one RCM	–5 to 20%			
					+/–	+ in southern UK and southern Sweden	–20 to 5%			
Muller et al. (2019)	Europe	+/–	+ in southern UK and Denmark	–3 to 2%	+/–	+ in southern UK and Denmark	–6 to 2%			
Després and Adamovic (2020)	EU	n.c.			n.c.					
Western Central Europe										
Tobin et al. (2018a)	EU and Switzerland	–		–3 to 0%	–		–3 to –1%	–		–4 to –1%
Jerez et al. (2015)	Europe				–	Negligible changes over France	–10 to 0%	–	Uncertain changes over western France	–10 to 0%
Gutiérrez et al. (2020)	Europe				+	Two RCMs (including aerosols); in RACMOE22, increases to 15%	5 to 30%			
					+/–	Four RCMs + over France	–15 to 5%			
Muller et al. (2019)	Europe	+		1 to 2.5%	+		0 to 3%			
Després and Adamovic (2020)	EU	n.c.			n.c.					
Southern Europe										
Tobin et al. (2018a)	EU and Switzerland	–		–1 to 0%	–		–1 to 0%	–		–1 to 0%
Jerez et al. (2015)	Europe				–	Uncertain changes over most of the Iberian Peninsula	–5 to 0%	–	Negligible changes over most of the Iberian Peninsula	–5 to 0%
Gutiérrez et al. (2020)	Europe				+	Two RCMs (including aerosols)	5 to 25%			
					+/–	Four RCMs; + over most of the area	–5 to 5%			
Muller et al. (2019)	Europe	+		0.5 to 2.5%	+		1 to 3%			
Després and Adamovic (2020)	EU	n.c.			n.c.					
Eastern Europe										
Jerez et al. (2015)	Europe				–		–10 to –5%	–	Higher decrease in northwest Russia	–15 to –5%
Gutiérrez et al. (2020)	Europe				+	Two RCMs (including aerosols)	5 to 20%			
					–	Four RCMs	–15 to –5%			

Sub-region	Area in study	Solar power potential (magnitude of change)								
		1.5°C			2°C			≥3°C		
Muller et al. (2019)	Europe	–		−3 to 0%	–		−6 to −2%			
Després and Adamovic (2020)	EU	n.c.			n.c.			n.c.		

Notes:

+: increase, –: decrease, +/–: increase in some regions and decrease in others, n.c.: no change

(a) In many studies, changes are provided in map format and thus figures in this table are our own interpretation of these map-based findings. Ranges illustrate variations within sub-regions. Values correspond to ensemble means, unless characterised otherwise.

(b) Measurement units for magnitude of change are as follows:

Tobin et al. (2018): PV power production; Jerez et al. (2015): PV potential production; Gutiérrez et al. (2020): surface solar radiation (and hence PV potential production); Müller et al. (2019: yearly PV production; Després and Adamovic (2020): electricity production from PV.

(c) The sign and magnitude presented in the first line for Gutiérrez et al. (2020) corresponds only to the range values for the two RCMs which include the effect of aerosols (i.e., ALADIN53 and RACMO22E), while the results in the second line corresponds to the range values for the other four RCMs explored in this study.

Table SM13.11 | Sign and magnitude of future change in hydropower potential under global warming levels (Figure 13.16)

Sub-region	Area in study	Hydropower potential (magnitude of change)								
		1.5°C			2°C			≥3°C		
Northern Europe										
Tobin et al. (2018a)	EU and Switzerland	+	Lowest in UK and Ireland	3 to 17%	+	Lowest in UK and Ireland	3 to 15%	+	Lowest in UK and Ireland; some models predict >30%	5 to 21%
van Vliet et al. (2016a)	Global (including Europe)				+/–	5 to 20% in northern Scandinavia, ±5% in most of the rest	−20 to 20%	+/–	5–20% in most of Norway, Sweden, northern Finland and northern UK; −20 to −5% in very few areas	−20 to 20%
van Vliet et al. (2016c)	Global (including Europe)				+/–	High increase in northern Scandinavia	−10 to >15%			
Després and Adamovic (2020)	EU	+		0 to 4%	+		1 to 7%	+		2 to 13%
Western Central Europe										
Tobin et al. (2018a)	EU and Switzerland	+		3 to 9%	+/–	– only in France; highest + in Czech Republic and Poland	−1 to 15%	+/–	– only in France; highest + in Czech Republic and Poland	−5 to 12%
van Vliet et al. (2016a)	Global (including Europe)				+/–	−5 to 5% only in Germany; −40 to −20% in Bulgaria, Romania and parts of Ukraine	−40 to 5%	+/–	−5 to 5% only in coastal Germany and Poland; −60 to −20% in most areas	−60 to 5%
van Vliet et al. (2016c)	Global (including Europe)				–		−15 to −5%			
Anghileri et al. (2018)	Alps	–		−27%						
Bombelli et al. (2019)	Italian Alps	+	−9.16% (CCSM4), 1.85% (EC-EARTH), 14.65% (ECHAM6), → 2.5% (mean)		+	0.03% (CCSM4), 10.72% (EC-EARTH), 8.33% (ECHAM6), → 6.4% (mean)		–	−6.3% (CCSM4), 0.23% (EC-EARTH), −7.23% (ECHAM6), → −4.4% (mean)	
Patro et al. (2018)	Italian Alps	+/–	+ when glacier area is <10% of total basin area	−32 to 5%	+/–	+ when glacier area is <10% of total basin area	−23 to 1%	+/–	+ when glacier area is <10% of total basin area	−40 to 6%

Sub-region	Area in study	Hydropower potential (magnitude of change)								
		1.5°C			2°C			≥3°C		
Stucchi et al. (2019)	Italian Alps	–	–25% (CCSM4), –14% (EC-EARTH), –10% (ECHAM6), → –16.3% (mean)		–	–28% (CCSM4), –10% (EC-EARTH), –13% (ECHAM6), → –17% (mean)		–	–27% (CCSM4), –23% (EC-EARTH), –33% (ECHAM6), → –28% (mean)	
Adynkiewicz-Piragas and Miszuk (2020)	Germany, Poland				–		–10 to 0%	–		–34 to –16%
Després and Adamovic (2020)	EU	+		0 to 1% (median values)	+		2 to 4% (median values)	+		1% (median value)
Southern Europe										
Tobin et al. (2018a)	EU and Switzerland	+/–	+ only in Italy and Slovenia; decrease >10% in Greece, Spain and Portugal in some models	–7 to 5%	+/–	+ only in Italy and Slovenia	–10 to 2%	+/–	+ only in Slovenia; decrease >20% in Greece, Spain and Portugal in some models	–18 to 2%
van Vliet et al. (2016a)	Global (including Europe)				–	–20 to –5% only in Italy	–40 to –5%	–		–60 to –40%
van Vliet et al. (2016c)	Global (including Europe)				–		< –15 to –10%			
Lobanova et al. (2016)	Portugal (Tagus)	–		–50 to –10%	–		–50 to –10%	–		–60 to –40%
Solaun and Cerdá (2017)	Spain	–		–25 to –5%	–		–30 to –10%	–		–49 to –30%
Després and Adamovic (2020)	EU	–		–1% (median value)	–		–3% (median value)	–		–2% (median value); may reach –13% under extreme events)
Eastern Europe										
van Vliet et al. (2016a)	Global (including Europe)				+/–	>5% in northern Russia, < –5% in western Russia	–20 to 20%	+/–	–5 to 5% in most of the areas	–20 to 20%
van Vliet et al. (2016c)	Global (including Europe)				+/–	+ in northern Russia	–10 to 15%			
Akentieva et al. (2014)	Russia	+/–		–8 to 14%	+/–		–10 to 18%			

Notes:

+: increase, –: decrease, +/–: increase in some regions and decrease in others, n.c.: no change

(a) In many studies, changes are provided in map format and thus figures in this table are our own interpretation of these map-based findings. Ranges illustrate variations within sub-regions. Values correspond to ensemble means, unless characterised otherwise.

(b) Measurement units for magnitude of change are as follows:

Tobin et al. (2018): hydropower production; van Vliet et al. (2016a): gross hydropower potential; van Vliet et al. (2016b): annual mean usable capacity of current hydropower plants; Després and Adamovic (2020): electricity production from existing hydropower plants; Anghileri et al. (2018): electricity production; Bombelli et al. (2019): yearly average energy production; Patro et al. (2018): water volume used for energy production in hydropower plants; Stucchi et al. (2019): energy production; Adynkiewicz-Piragas and Miszuk (2020): energy production; Després and Adamovic (2020): electricity production; Lobanova et al. (2016): hydropower produced; Akentieva et al. (2014); average annual electricity production.

Table SM13.12 | Sign and magnitude of future change in bioenergy crops (rapeseed) potential under global warming levels (Figure 13.16)

Sub-region	Area in study	Bioenergy potential (magnitude of change)				
		1.5°C		2°C	≥3°C	
Western Central Europe						
Jaime et al. (2018)	Global (including Europe)	–	EU countries: –8.5% (CSIRO Mk2), –9% (Hadley CM3), –10.2% (MPI ECHAM4), → –9.2% (mean)		–	EU countries: –7.6% (CSIRO Mk2), –22.2% (Hadley CM3), –24.9% (MPI ECHAM4), → –18.2% (mean)
Cronin et al. (2020)	Global (including Europe)				+	4% (no land restrictions both in past and future)
						27% (SSP5, where urban, food agricultural land and protected areas are excluded both in past and future)
						1% (SSP5, but forest areas are not excluded both in past and future)
Eastern Europe						
Jaime et al. (2018)	Global (including Europe)	+	Rest of Europe (mainly Russia): 32.5% (CSIRO Mk2), 41.6% (Hadley CM3), 54.4% (MPI ECHAM4), → 42.8% (mean)		+	Rest of Europe (mainly Russia): 15.8% (CSIRO Mk2), 44.2% (Hadley CM3), 58.8% (MPI ECHAM4), → 39.6% (mean)
Cronin et al. (2020)	Global (including Europe)				+	Russia (whole): 210% (no land restrictions both in past and future)
						Russia (whole): 219% (SSP5, where urban, food agricultural land and protected areas are excluded both in past and future)
						Russia (whole): 431% (SSP5, but forest areas are not excluded both in past and future)

Notes:

+: increase, –: decrease, +/–: increase in some regions and decrease in others, n.c.: no change

(a) Measurement units for magnitude of change are as follows: Jaime et al. (2018): percentage of change of land suitable for rapeseed cultivation (to produce biofuels) compared with 1996; Cronin et al. (2020): percentage of change of total land that is moderately or highly suitable for energy crops cultivation (15 crops) compared with 1980–2009.

(b) Jaime et al. (2018) present results for EU countries as a total. According to the study, most suitable land in the EU is, and will remain, in Western Central Europe, and therefore the whole percentage change in the EU has been allocated to Western Central Europe. Note that that 'Eastern Europe' in the study corresponds to 'Western Central Europe' in the present IPCC Assessment Report.

(c) The study also presents results for the whole suitable area for rapeseed cultivation, and thus by subtracting the EU figures, the change in the rest of Europe and Western Asia can be estimated. The figures for Eastern Europe correspond to the total change in the rest of Europe and Western Asia and thus are overestimated.

(d) Cronin et al. (2020) present results for different sub-regions of Europe which, however, do not match the definitions adopted in this IPCC chapter; therefore, the reference's results–calculated from the data provided on the reference's supplementary material–for Russia are presented under Eastern Europe, while EEU, FSU and WEU are presented as an aggregated figure under Western Central Europe.

Table SM13.13 | Sign and magnitude of future change in thermoelectric power capacity under global warming levels (Figure 13.16)

Sub-region	Area in study	Thermoelectric power capacity (magnitude of change)								
		1.5°C			2°C			≥3°C		
Northern Europe										
Tobin et al. (2018a)	EU and Switzerland	–		–7 to –2%	–		–10 to –3%	–		–15 to –7%
Després and Adamovic (2020)	EU	–		–4 to 0%	–		–6 to 0%	–		–15 to 0%
van Vliet et al. (2016c)	Global (including Europe)				–		<–15%			
Byers et al. (2020)	UK				–	Cumulative impacts over 32 plants	–18% (p5), –20% (p50), –45% (p95)	–	Cumulative impacts over 32 plants	–36% (p5), –41% (p50), –58% (p95)

Sub-region	Area in study	Thermoelectric power capacity (magnitude of change)								
		1.5°C			2°C			≥3°C		
Western Central Europe										
Tobin et al. (2018a)	EU and Switzerland	–		–8 to –5%	–		–13 to –6%	–		–18 to –11%
Després and Adamovic (2020)	EU	n.c.		0%	–		~0%	–	– for nuclear plants	–2%
van Vliet et al. (2016c)	Global (including Europe)				–		<–15%			
Southern Europe										
Tobin et al. (2018a)	EU and Switzerland	–		–7 to –1%	–	All countries except Portugal <–8%	–12 to –1%	–	All countries except Portugal <–14%	–18 to –1%
Després and Adamovic (2020)	EU	–	– for nuclear plants; figure results from impacts on whole energy system	–2 to 0%	–	– for nuclear plants; figure results from impacts on whole energy system; –13% under extreme events	–5 to –1% (and may reach –12% under extreme events)	–	– for nuclear plants; figure results from impacts on whole energy system; –12% under extreme events	–8 to –2% (and may reach –12% under extreme events)
van Vliet et al. (2016c)	Global (including Europe)				–		<–15%			
Payet-Burin et al. (2018)	Iberian Peninsula	–	Average for all freshwater-cooled plants: –18 to –6% (annual) W: –12 to –1%, S: –30 to –16%							
			Once-through cooling: –16 to –11% (annual) S: –40 to –31% closed-circuit cooling: <–0.5%							
Eastern Europe										
van Vliet et al. (2016c)	Global (including Europe)				–		–10 to –5%			
Klimenko et al. (2018)	Russia				–	Efficiency reduction by 0.2–0.6% per +1°C	–1.2 to –0.4% (if a +2°C is considered)	–	Efficiency reduction by 0.2–0.6% per +1°C	Up to –2% (if a +3°C is considered)

Notes:

+: increase, –: decrease, +/–: increase in some regions and decrease in others, n.c.: no change, S: summer, W: winter, p5: 5th percentile, p50: 50th percentile (median), p95: 95th percentile.

(a) In many studies, changes are provided in map format and thus figures in this table are our own interpretation of these map-based findings. Ranges illustrate variations within sub-regions. Values correspond to ensemble means, unless characterised otherwise.

(b) Measurement units for magnitude of change are as follows:

Tobin et al. (2018): thermoelectric power production; van Vliet et al. (2016b): annual mean usable capacity of thermoelectric power plants; Després and Adamovic (2020): electricity production from existing thermoelectric plants (including nuclear); Anghileri et al. (2018): electricity production; Bombelli et al. (2019): yearly average energy production; Patro et al. (2018): water volume used for energy production in hydropower plants; Stucchi et al. (2019): energy production; Adynkiewicz-Piragas and Miszuk (2020): energy production; Després and Adamovic (2020): electricity production; Lobanova et al. (2016): hydropower produced; Akentieva et al. (2014): average annual electricity production; Payet-Burin et al. (2018): available power plant capacity of freshwater-cooled thermal power plants; Byers et al. (2020): available power plant capacity at 99th percentile extreme day; Klimenko et al. (2018): power plant efficiency.

Table SM13.14 | Examples of adaptation options for reducing sectoral climate-change risks (Figure 13.19)

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Thermoelectric power	Reduction/ interruption of operation due to water cooling constraints	Replacement of once-through cooling by cooling towers; dry air-cooling; seawater cooling (for coastal plants); replacement by new, better-adapted plants (Gasbarro et al., 2016; Behrens et al., 2017; EEA, 2019a; IAEA, 2019)	The choice of electricity producers between options is guided mainly by the economics of adaptation technologies, and less by the supply of information on future climate change (Bogmans et al., 2017). Costs for retrofitting cooling are site specific and increase with the distance to water bodies, needs for additional structures and the plant's age (Sieber, 2013). Dry air-cooling for new plants is 3–4 times higher than wet recirculating system and 4–5.5 times higher than once-through cooling (IAEA, 2019), and could result in 10% efficiency losses (EEA, 2019a).
		Switching to alternative-generation technologies with low water use, (e.g., wind, solar PV) (Gasbarro et al., 2016; Porfiriev et al., 2017; EEA, 2019a)	Fragmentation of policy frameworks for energy and water make cohesive energy and water management difficult (Byers et al., 2015; Behrens et al., 2017). Ignoring the impact of climate-induced water constraints may significantly increase the energy system costs (Khan et al., 2016).
		Inter-basin water transfer (Koch et al., 2014)	
		Use of 'non-traditional' water sources (e.g., recirculation of water from oil and gas fields or coal mines, treated wastewater from nearby cities, desalination, water reuse) (Sieber, 2013; Gasbarro et al., 2016)	Nearby sources of 'non-traditional' waters may not exist or may be of insufficient capacity.
		Shift part of power production to estuaries or coasts (Byers et al., 2015)	Its implementation to high-demand areas could bring significant nationwide water reductions (Byers et al., 2015), provided that recipient plants can undertake the extra production.
		Improved electricity interconnections (Behrens et al., 2017)	There are high investment costs.
		Demand management measures (e.g., smart grid/meters, pricing options, energy efficiency) to reduce the economic losses during power curtailment (Gasbarro et al., 2016)	This can be an effective option, particularly under low climate-change scenarios (Hanski et al., 2018).
		Institutional measures (e.g., water temperature cap, heat-load plan, contract between environmental regulator and electricity producers)	The efficiency of institutional adaptation options may differ depending on the increase in heatwave intensity, frequency or both (Eisenack, 2016). Stakeholder engagement (e.g., increase awareness of decreasing water flows, cooperation) to prevent the conflicts with the local communities in case of water curtailments is helpful (Gasbarro et al., 2016)
Hydropower	Reduced production due to lower streamflow	Adjusted hydropower management (Gaudard et al., 2013; EEA, 2019a)	Optimising the hydraulic head and the turbine schedule with respect to the prices could reduce power losses by up to 35% (Gaudard et al., 2013).
	Increased risk of damage from flooding	Adjusted hydropower management (Aparicio, 2017; Ranzani et al., 2018)	Adaptive strategies in the management of reservoirs could reduce (but not prevent) revenue losses (Ranzani et al., 2018).
		Recalibration of spillways (e.g., through piano-key wires, concrete or metal fuse gates)	Recalibration systems have been implemented successfully in hydropower facilities in Europe and outside Europe (EEA, 2019a).
		Increase the capacity of existing hydropower plants (i.e. increase installed turbine capacity, increase reservoir storage)	This option has been implemented in some northern European hydropower plants (EEA, 2016a).
		Hydropower operational warning systems, monitoring of snowpack and river flows, forecast of high water flows	Hydropower forecasting faces key challenges related to integration of state-of-the-art weather services, data assimilation schemes, links between forecast quality and value, and enhancement of risk-based decision making (Boucher and Ramos, 2018).

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Electricity transmission and distribution	Power outages due to damage to transmission lines and power stations from extreme winds, storm surges, floods and very high temperatures	Construction of new substations and overhead lines (providing additional paths to transfer power in case of a transmission line failure); improve old overhead lines and substations (Gasbarro et al., 2016; Fu et al., 2018)	Efficiency increases when construction of new lines and stations occurs to decentralised power systems, while improvement of existing lines and stations is less efficient (Fu et al., 2018). The contribution of substations' refurbishment in building flood resilience depends on the degree of protection of critical substations which may not necessarily be the most vulnerable to high water levels (Bollinger and Dijkema, 2016). The willingness to pay (WTP) to avoid power outage is higher for older people, women and urban residents; risk perceptions are greatly influenced by current regional temperatures; and under strong warming the WTP increases in summer and decreases in winter in all countries, particularly in the north (Cohen et al., 2018a). Experience with previous power cuts significantly enables resilience (Ghanem et al., 2016; Cohen et al., 2018a).
		Vegetation management	New technologies (e.g., Lidar) allow to reduce the need for time-consuming and labour-intensive traditional verification and to provide reliable input for guiding tree trimming; however, their implementation may require significant changes of management practices at the utility level.
		Turning, partially or totally, of overhead lines into underground cables (Wang et al., 2016; Ciasca et al., 2017)	There is high installation cost and potentially long implementation time, depending on the area covered and the length of cables (EEA, 2019a). Selective undergrounding of line sections exposed to higher risk or harder to access can be a cost-effective adaptation strategy (Wang et al., 2016). For new lines, there are potentially long permit processes and public opposition (Wang et al., 2016; Ciasca et al., 2017).
		Locating assets above flood level, flood barriers, relocation of assets (Bollinger and Dijkema, 2016; Wang et al., 2016; Thacker et al., 2018)	There are high investment costs for existing assets (Wang et al., 2016) and long implementation time (EEA, 2020c). transmission system operators often prefer to combine investments in flood defences with major renovations or refurbishments to substations, and consequently prioritisation often occurs based on factors (e.g., its age) unrelated to a substation's criticality (Bollinger and Dijkema, 2016; Wang et al., 2016). Assets' relocation is almost always not cost beneficial (Thacker et al., 2018).
		Distribution circuit segregation and automation (Wang et al., 2016).	
		Increase in the height of poles supporting power lines, installation of conductors with hotter operating limits, use of 'low-sag' conductors (EEA, 2019a)	There are legal requirements on minimum pole-height-support adaptation (EEA, 2019a).
	Reliability problems in electricity networks due to increased peak load for cooling	Strict efficiency standards for cooling equipment (EEA, 2019a; Palkowski et al., 2019)	Reliability can be increased through measures reducing cooling demand, such as improved building design, water cooling technologies for thermoelectric generation that do not use electricity (e.g., heat-driven absorption cooling), or direct utilisation of cooling water where available (EEA, 2019a).
		Increase in transmission capacity, including international linkages	
		Increase in backup capacity	
Transport	Reduction/ interruption of transportation due to damaged infrastructure and/or traffic disruption as a result of intense rain, flooding and heatwaves	Broad range of options (EEA, 2014; Frolov et al., 2014; Burbidge, 2015; Stamos et al., 2015; van Slobbe et al., 2016; Bachner, 2017):	Particularly in road transport, measures have also economy-wide feedback effects which must be considered when assessing adaptation benefits (Bachner, 2017). Nevertheless, as it is difficult to quantify the benefits and costs of adaptation measures in transport, cost–benefit analyses need to be performed on a case study level (Doll et al., 2014).
		(a) Infrastructure construction/retrofitting (e.g., enlargement of drainage systems, measures to reduce slippery roads, raise links above flood level)	As 'soft' adaptation options (e.g., ICT) have already been implemented to a large extent in railways, investments in advanced protection systems (e.g., tunnels, protection walls and enlarged drainage) are necessary to support proactive maintenance strategies (Doll et al., 2014). Improving drainage or elevating critical road links can be cost-effective but requires analysis at the city level (Pregnolato et al., 2017). Adaptations in vessel design may reduce the vulnerability to low depth, but with a trade-off with performance in times of sufficient discharge (van Slobbe et al., 2016).
		(b) Improved maintenance (e.g., vegetation management, visual road inspection)	Network maintenance can be a more cost-efficient way to reduce short- and medium-term damage risks (Doll et al., 2014).
		(c) ICT and users (e.g., early warning on adverse weather, weather forecasting)	Lack of coherence between the climate adaptation plans of companies operating major transport infrastructure and their neighbouring municipalities may reduce the effectiveness of adaptation actions undertaken by the transport sector (EEA, 2014).
		(d) Modal shifts	
		(e) Technological innovations (e.g., heat-resistant pavement materials, materials designed for a greater number of cycles of freezing and thawing, logistic chains)	Some of the new pavement materials may increase noise levels in urban areas (Enríquez-de-Salamanca (2019).

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Transport	Reduction/ interruption of transportation due to damaged infrastructure and/or traffic disruption as a result of intense rain, flooding and heatwaves	(f) Revising operational guidelines and standards	The location-specific nature of weather impacts requires analysis and response also at the route level to ensure that investments in flood protection are cost-effective (EEA, 2020c). Dynamic heat management can reduce the heat-related disruption from unnecessary emergency speed restrictions on railway networks (Ferranti et al., 2016).
	Reduction of thermal comfort of passengers in railways and metro lines due to higher temperatures	Saloon cooling, cooling of platforms and tunnels (Jenkins et al., 2014a)	Saloon cooling alone may not be sufficient to maintain comfortable thermal conditions for some lines under high emission scenarios (Jenkins et al., 2014b).
Winter tourism	Reduction/ interruption of operation due to lack of snow	Snowmaking (including application of automated snowmaking systems)	High investment cost (i.e., for development of water supply systems, purchase and installation of snow cannons) and increased operational costs (Campos Rodrigues et al., 2018; Scott et al., 2019) are potential barriers. Increased snowmaking can maintain snow reliability under low warming but is not sufficient under high-end warming (Steiger and Scott, 2020). Snowmaking was found to reduce guest loyalty of skiing destinations in some customer segments by affecting the natural scenery and raising prices (Bausch et al., 2019).
		Protection and conservation of snowpack (e.g., water drainage, modification of the ski-run slopes, protection from avalanches, protection or storage of snow during the non-ski seasons); snow farming (Steiger and Scott, 2020)	Several techniques are available.
		Expansion of skiable area	Need of substantial investments and free areas has adverse impacts (e.g., land-use conflicts, impacts of construction on natural areas, impacts on the landscape quality, increased water and energy use) (Campos Rodrigues et al., 2018).
		Nocturnal skiing (Campos Rodrigues et al., 2018)	Nocturnal skiing is already offered at some ski resorts, but it can compensate for a small part of potential losses due to adverse weather and safety limitations (Campos Rodrigues et al., 2018).
		Shift to other ski destinations (spatial substitution)	The attachment ('loyalty') of glacier skiers to their favourite leisure destination, gender, demographics (i.e., age) and perceptions towards environmental sustainability were found to be important in guiding adaptation preferences (Demiroglu et al., 2018).
		Diversification of snow-based activities	Diversification may be too costly for some resorts. Skiing in indoor slopes may be the least preferred option for skiers, while other winter activities (e.g., snowboarding, downhill skiing) may not be effective adaptation options as skiing is perceived as a necessity in some countries (Falk, 2015; Falk and Scaglione, 2018).
		Transformation to multi-recreational mountain resorts, compensating non-snow activities	Transformation can take place by diversifying the offer in winter towards nature-based activities or place-bound products beyond winter sports (Bausch and Gartner, 2020) and by developing year-round tourism and snow-independent tourism products (Steiger and Scott, 2020). Transformation may be too costly for some resorts (Campos Rodrigues et al., 2018). Non-snow activities are not appealing to people for whom skiing is the main activity of their winter holiday (Steiger and Scott, 2020). Cultural differences affect the effectiveness of compensating activities (Landauer et al., 2013).
		Management options (e.g., grouping of resorts, pricing strategies) (Campos Rodrigues et al., 2018)	Price discounts are effective under less severe warming scenarios (Steiger et al., 2020). Price discounts in ski lift tickets may not be enough to attract foreign visitors (Falk and Scaglione, 2018).

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Coastal and summer tourism; other forms of tourism	Loss of beaches/ coasts due to SLR and increased erosion	Hard defences (e.g., seawalls)	It is a measure that has been widely applied in Europe, but generally with no concern for future climate-change impacts. It also requires high investments, proper maintenance (which is costly) and can affect sediment transport and coastal erosion (Pranzini et al., 2015).
		Soft measures (e.g., artificial beach nourishment, dune planting) (Pranzini et al., 2015; Jiménez et al., 2017)	Selective sand nourishment is common in Europe (Pranzini et al., 2015), as in Spain where more than 22 million m^3 of sand have been deposited on the Catalan coast during the past 30 years (Jiménez and Valdemoro, 2019). There is often reduced availability and there are high costs of fill material. Potential governance difficulties also exist (e.g., lack of well-defined roles in coordinating nearshore activities, division of costs between government, private owners and local communities).
		Inland shift of tourism activities	This may not be possible due to land-use and financial constraints, as well as environmental and administrative regulations.
	Disruption of tourism activities due to higher temperatures	Temporal shift/extension of recreational activities outside the summer period (e.g., transition-time tourism, year-round tourism)	Potential barriers include organisational issues and the inability or reluctance of clientele (Mourey et al., 2020). Limiting factors to be considered include cost, school holidays or work (Brosy et al., 2014).
	Disruption of tourism activities due to water scarcity	Water supply and demand measures (e.g., desalination, rainwater harvesting, water remediation and water reuse, water saving devices) (Michailidou et al., 2016)	Identification of the suitable alternatives implies consideration of several and often conflicting criteria and stakeholder involvement (Michailidou et al., 2016).
Business	Reduction/ interruption of operation due to extreme events; asset damage; reduced sales due to lower demand; health and safety risks for staff	Individual adaptation measures at the enterprise and cluster levels: general measures (e.g., risk assessment and monitoring, technical solutions, reduction of exposure through geographical decisions, shifting and sharing of risks, disaster relief and business continuity, portfolio diversification, and cooperation) (Pinkse and Gasbarro (2019)	Potential barriers include a lack of human or financial resources and scientific or technical knowledge to understand climate-change risks (Aguinaldo et al., 2019); and also limited knowledge on scale of assessment, evidence base, adaptation response, scope of impacts, interdependencies and public policy (Surminski et al., 2018). The cluster approach allows to overcome the lack of resources and knowledge to address climate risks and adaptation options, which characterise particularly small and medium-size enterprises (Aguinaldo et al., 2019).
		Individual adaptation at the enterprise and cluster levels: measures against heatwaves (e.g., shielding or reflective surfaces, use of 'cool' materials, green walls, green parking and draining floors, energy management system, changes in working practices, appropriate clothing) (Ciscar et al., 2018; IRIS LIFE project, 2019)	Changes in working practices for outdoor workers: more frequent and longer breaks during the hottest parts of the day; earlier starts and/or later ends to the working day; and night working. Other changes: provide drinking water; scheduling heavy work during the cooler parts of the day or reducing work during the hottest part of the day; alternate work and rest periods; wearing appropriate clothing; and employees' education. Shifting the working hours from daytime to nighttime could entail side effects such as chronic fatigue, anxiety, depression and noise pollution for nearby residents (Ciscar et al., 2018).
		Individual adaptation at the enterprise and cluster levels: measures against storms	Potential measures include closing tunnel connection in case of strong wind, tree pruning, limiting storage of materials outside the building, shielding surfaces and roof anchorage (IRIS LIFE project, 2019).
		Individual adaptation at the enterprise and cluster levels: measures against heavy rains and floods	Potential measures include alert systems, anti-reflux valves, temporary meteoric water storage areas, anti-flooding bulkheads and storage of materials at a safe height from the ground (IRIS LIFE project, 2019).
		Individual adaptation at the enterprise and cluster levels: measures against drought	Drought causes reduced water availability for the processes within the factories. Potential measures include treatment and reuse of wastewater as well as sector-specific measures for reducing water consumption (Alkayal et al., 2015). In food and beverage, options include implementation of Best Available Techniques, sector-specific measures for meat and poultry, fish, fruits and vegetables, dairy products and drink processing sectors (Valta et al., 2016).
		Corporate adaptation	Corporate strategies to climate risks still predominantly focus on mitigation (Sakhel (2017; Pinkse and Gasbarro, 2019). It is dominated by surveillance of climatic changes, climate-proofing production facilities and assets, and supply chain management (Sakhel (2017).
Banking and finance	Risk of instability of the financial system due to damage caused by climate extremes	Extension of financial regulations and requirements for risk monitoring towards climate-related risks, such as climate-related stress tests (TCFD, 2017; D'Orazio and Popoyan, 2019)	Only in a few European countries are such regulations in place, but they are voluntary (D'Orazio and Popoyan, 2019).
Insurance	Risk of insurance default	Public reinsurance	
		Extension of risk monitoring towards climate-related risks	

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Cities	Reduced indoor and outdoor thermal comfort and power outages due to heatwaves[a]	Passive and active cooling measures in buildings (e.g., air conditioning, ventilation, shading)	Coping appraisal is a strong predictor for citizens' motivation to adapt, while elderly people are less motivated (Murtagh et al., 2019). Though necessary, natural ventilation alone cannot fully mitigate overheating (Dodoo and Gustavsson, 2016; Heracleous and Michael, 2018; Dino and Meral Akgül, 2019; Shen et al., 2020), and its effectiveness is strongly affected by occupants' behaviour (Tillson et al., 2013; van Hooff et al., 2014), while a combination of shading and ventilation (including nighttime) is needed (Ibrahim and Pelsmakers, 2018). Installation of air conditioning may be too costly for many households (Thomson et al., 2019). Large increase of air conditioning in densely populated areas may exacerbate the urban heat island and thus overheating (Kingsborough et al., 2017), and increases pressure on electricity systems.
		Interventions at the buildings' shell (e.g., improving insulation, increasing thermal mass, use of phase-change materials)	Addition of insulation in poorly ventilated and shaded buildings may increase overheating. Altering the thermal mass is much harder in older buildings (Tillson et al., 2013). Phase-change materials could significantly reduce the cooling load but is a relatively new technology to the construction industry, with many uncertainties (e.g., future prices, long-term durability, energy cost) (Sajjadian et al., 2015). Material changes to buildings are often prohibited by restrictive tenancy relations (Thomson et al., 2019).
		Green, blue and grey infrastructure (e.g., green areas, green roofs and walls, cool roofs and façades, cool pavements)	Climatic conditions may affect performance of options (Ward et al., 2016). On-site water reuse systems can provide supplementary water to green roofs and walls, gardens and other smaller-scale urban nature-based solutions on an as-needed basis. The cooling potential of plants in green roofs or walls is influenced by the choice of plant species (Cameron et al., 2014). Cool roofs are less expensive and easier to apply than green roofs (Carvalho et al., 2017a). People's willingness to pay for green infrastructure (GI) has been found to be mostly related to income and ethnicity, while citizens are willing to support climate adaptation through GI as long as the GI is multifunctional (i.e., comes with recreational and aesthetic benefits) (Derkzen et al., 2017). Urban governance mechanisms and institutional barriers to GI planning need additional research (Emmanuel and Loconsole, 2015). Cool roofs are an established technology, but this is not yet the case for cool pavement materials which may cause glare problems or excessive illumination levels (Carnielo and Zinzi (2013). Options are not easily transferable between countries or even cities (Hintz et al., 2018).
		Update building standards to consider the expected increase of extreme summer temperatures and the consequent increase of energy demand for cooling	Standards considering climate change and outdoor climate conditions, and realistic assumptions in terms of occupant adaptations, are needed (Mulville and Stravoravdis, 2016; Sánchez-García et al., 2020; Shen et al., 2020). Standards should consider regional differences (Frolov et al., 2014).
		Watering of roads and pavements	Emergency options are needed during heatwaves, but not a long-term adaptation option (Hendel et al., 2017; Enríquez-de-Salamanca, 2019). Optimisation of possible watering methods has only rarely been conducted, while water consumption is an issue (Hendel et al., 2015).
		Escape to nearby mountainous regions (Juschten et al. (2019b)	Mostly motivated by social and subjective norms, past experience with heat stress, outdoor sports as a travel motive, previous visits to the destination, positive media coverage and perceived behaviour control (Juschten et al., 2019a).
	Reduced water supply due to drought	Water demand management (Buurman et al., 2017)	Voluntary or enforced water conservation is a potential measure. There is a high degree of uncertainty regarding effectiveness, but when coupled with new water reuse infrastructure, it could keep the probability of exceeding the target frequency of an emergency drought order below 0.01 in London under severe drought by 2100 for a medium-emissions scenario and high population growth (Kingsborough et al., 2016).
		Expansion of water supply (Buurman et al., 2017)	Water reuse, new water reservoirs, inter-basin transfers, desalination and artificial aquifers are potential measures. This is less flexible as it requires commitment to supply infrastructure, which can be maladaptive under increasing water demand (Kingsborough et al., 2016).
	Corrosion of buildings due to permafrost and thaw melting	Use of materials with proper resistance to freezing–thawing cycles (Frolov et al., 2014)	Development of an assessment methodology and database on the durability of materials under various climatic conditions is needed to support the selection of optimal materials under the future climate. Regular updating of regulatory parameters based on observational data is also needed (Frolov et al., 2014).
		Increase in corrosion resistance of structural elements (Frolov et al., 2014)	
		Design solutions that prohibit an increase in moisture content in building structures (Frolov et al., 2014)	

Sector	Risk and cause	Examples of adaptation options	Elements related to the implementation of adaptation options
Cities	Damage to settlements and infrastructure due to flooding	Building new flood defences (e.g., dikes)	Costs for maintaining the baseline flood protection level under climate change (and introducing a minimum of 100 years of protection) through defences would not outweigh benefits for many countries before 2030 under different RCP or SSP scenarios, while in 2080 adaptation benefits would exceed costs in almost all countries (Bouwer et al., 2018). Update and increased maintenance of storm barriers comes along with concerns on their environmental impacts as in St Petersburg (Rodionov, 2016). Decision making under deep-uncertainty approaches can be applied to deal with the uncertainties of climatic projections (Babovic et al., 2018). Information such as a high-resolution European and Mediterranean flash floods dataset can provide input to impact assessment, modelling and forecast (Amponsah et al., 2018).
		Heightening and/or strengthening of existing dikes, dams and levees; widening of river floodplains and reduction of obstructions in floodplains (Bouwer et al., 2018); updating the urban drainage system (Bodoque et al., 2019)	
		Flood protection measures at the building and household level, such as dry-proofing (e.g., sealing walls with waterproof coatings, impermeable layering of masonry, sealants for openings), wet-proofing (e.g., building elevation, use of water-resistant materials), emergency measures (e.g., mobile flood barriers, sandbags), securement of sources of contamination	There is *high confidence* that past experience of damage strongly affects risk perception and hence motivation for adaptation (Baron and Petersen, 2015; Lujala et al., 2015; Osberghaus, 2015; Madsen et al., 2019); however, protection may be motivated mostly by coping and threat appraisal as well as trust in public institutions (Bamberg et al., 2017). Dry-proofing is costly and thus usually applied to new buildings (Bouwer et al., 2018). The level of wet-proofing differs significantly between locations (Koerth et al., 2013; Stojanov et al., 2015). Perceptions of flood risks, expected climate impacts, risk attitudes and geographical characteristics were found to be the most important determinants in the decision to invest in elevating houses (Botzen et al., 2013).
		Nature-based Solutions (NbS) to manage water runoff (e.g., multifunctional green spaces, wetlands, retention/detention and infiltration basins, rain gardens and green roofs)	Natural ecosystems remain under threat from changing climatic conditions. Potential barriers for development of green infrastructure for flood risk management include coordinating and convincing stakeholders, limitations of the existing legislations and difficulty in assessing non-monetary benefits (Liu and Jensen, 2018).
		Facilitation of recovery after climate extremes	The location and composition of urban green spaces is key for effective adaptation (García Sánchez et al., 2018).
		Increase in flood risk standards, land-use planning, risk zoning, dedicated flood management legislation	Measures that work well in one region may not be effective in another region facing different flood hazards, and thus building codes and all other flood risk management policies have to be region specific (Poussin et al., 2015). Legislation to delimit non-suitable land for urbanisation often shows a slow implementation (Pérez-Morales et al., 2018), although it can be very effective in reducing risks under climate change (Thieken et al., 2016). Under high SLR, risk zoning can be more effective than hard defences (Andersson-Sköld et al., 2015).
		Emergency plans, training for evacuations, early warning systems	Require that the role and responsibilities of the different administrative departments and organisations involved be well defined, and that there be a clear plan on how to manage the different stages in the recovery process (Adedeji et al., 2019).
		Planned relocation	Higher resistance was found among seafront residents, second-home occupants, homeowners, elderly and retired people, and multi-generation households (Dachary-Bernard et al., 2019; Rey-Valette et al., 2019; Seebauer and Winkler, 2020).
	Clay-related subsidence due to increased or extreme drought	Deeper foundations, trees or terraces around light buildings to keep humidity in soils and prevent ground motions	Clay-related subsidence risks can be managed by appropriate adaptation measures at building scales (*medium confidence*) (Pritchard et al., 2015).

Note:
(a) Heatwave warnings and heat action plans as means for adaptation are discussed in Section 13.7.2.

Table SM13.15 | Literature sources used in the assessment of feasibility and effectiveness of adaptation options for cities, settlements and key infrastructures in Europe (Figure 13.20)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Reduction of thermal comfort due to increasing temperatures and extreme heat	Interventions in the building shell	Tillson et al. (2013); Sajjadian et al. (2015); Ibrahim and Pelsmakers (2018); Domínguez-Amarillo et al. (2019)	Tillson et al. (2013); Sajjadian et al. (2015); Murtagh et al. (2019)	Sajjadian et al. (2015)	Ibrahim and Pelsmakers (2018); Murtagh et al. (2019)	Ibrahim and Pelsmakers (2018); Murtagh et al. (2019)		Tillson et al. (2013); Ibrahim and Pelsmakers (2018); Domínguez-Amarillo et al. (2019)
	Ventilation	Tillson et al. (2013); van Hooff et al. (2014); Dodoo and Gustavsson (2016); Mulville and Stravoravdis (2016); Hamdy et al. (2017); Zinzi et al. (2017); Heracleous and Michael (2018); Ibrahim and Pelsmakers (2018); Dino and Meral Akgül (2019); Thomson et al. (2019)	van Hooff et al. (2014); Murtagh et al. (2019)	van Hooff et al. (2014)	Tillson et al. (2013); Mulville and Stravoravdis (2016); Murtagh et al. (2019)	Tillson et al. (2013); van Hooff et al. (2014); Mulville and Stravoravdis (2016); Ibrahim and Pelsmakers (2018); Murtagh et al. (2019); Thomson et al. (2019)		Tillson et al. (2013); van Hooff et al. (2014); Ibrahim and Pelsmakers (2018)
	Air conditioning	Jenkins et al. (2014a); Dodoo and Gustavsson (2016); Dino and Meral Akgül (2019)	Ferrara and Fabrizio (2017); Thomson et al. (2017)			Thomson et al. (2019)		Jenkins et al. (2014a)
	Shading	Tillson et al. (2013); van Hooff et al. (2014); Dodoo and Gustavsson (2016); Zinzi et al. (2017); Ibrahim and Pelsmakers (2018)	Tillson et al. (2013); van Hooff et al. (2014); Murtagh et al. (2019)	van Hooff et al. (2014)	Murtagh et al. (2019); Thomson et al. (2019)	Tillson et al. (2013); Ibrahim and Pelsmakers (2018); Murtagh et al. (2019)		van Hooff et al. (2014); Thomson et al. (2019)
	Green roofs, green walls	Cameron et al. (2014); van Hooff et al. (2014); Virk et al. (2015); Carvalho et al. (2017a); de Munck et al. (2018)	Cameron et al. (2014); Virk et al. (2015); Carvalho et al. (2017a); de Munck et al. (2018)	Cameron et al. (2014); Carvalho et al. (2017a); de Munck et al. (2018)	Cameron et al. (2014); Virk et al. (2014)	Cameron et al. (2014); van Hooff et al. (2014); Virk et al. (2015); Carvalho et al. (2017a); Derkzen et al. (2017)	Virk et al. (2015)	van Hooff et al. (2014)
	Urban green spaces	Emmanuel and Loconsole (2015); Ward et al. (2016); Carvalho et al. (2017a); de Munck et al. (2018)	Carvalho et al. (2017a); de Munck et al. (2018)	Carvalho et al. (2017a); de Munck et al. (2018)	Emmanuel and Loconsole (2015)	Carvalho et al. (2017a); Derkzen et al. (2017); Thomson et al. (2019)	de Munck et al. (2018)	Emmanuel and Loconsole (2015); Carvalho et al. (2017a); de Munck et al. (2018); Thomson et al. (2019)
	Use of 'cool' paints and coatings	Carnielo and Zinzi (2013); van Hooff et al. (2014); Virk et al. (2014); Virk et al. (2015); Zinzi (2016); Carvalho et al. (2017a)	van Hooff et al. (2014); Virk et al. (2015); Carvalho et al. (2017a); Murtagh et al. (2019)	Carnielo and Zinzi (2013); Carvalho et al. (2017a)	Virk et al. (2014)	Carnielo and Zinzi (2013); Virk et al. (2015); Murtagh et al. (2019)		Zinzi (2016)
	Escape to nearby non-urban destinations					Juschten et al. (2019a); Juschten et al. (2019b)		

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Loss of critical services due to heatwaves and drought	Improvements in cooling systems	Jenkins et al. (2014a); Koch et al. (2014); Byers et al. (2015); Ferranti et al. (2016); Kingsborough et al. (2016); van Vliet et al. (2016b); Behrens et al. (2017); Bogmans et al. (2017)	Koch et al. (2014); van Vliet et al. (2016b); Behrens et al. (2017); Bogmans et al. (2017); EEA (2019a)	Sieber (2013); Ferranti et al. (2016)	Jenkins et al. (2014a); Koch et al. (2014); Byers et al. (2015); Hendel et al. (2016); Kingsborough et al. (2016); Behrens et al. (2017)			Sieber (2013); Koch et al. (2014); van Vliet et al. (2016b); Behrens et al. (2017)
	Shifting production to less water-intensive plants	Khan et al. (2016)	Khan et al. (2016); Behrens et al. (2017)	Khan et al. (2016)	Behrens et al. (2017)			
	Regulatory measures	Eisenack (2016)	Eisenack (2016)		Eisenack (2016)			
	Management measures	Gaudard et al. (2013); Hendel et al. (2015); Ferranti et al. (2016); Kingsborough et al. (2016); Ranzani et al. (2018); Wang et al. (2019)	Ferranti et al. (2016); Ranzani et al. (2018); Wang et al. (2019)	Hendel et al. (2015); Kingsborough et al. (2016)	Ferranti et al. (2016); EEA (2019a); Palkowski et al. (2019)		Hendel et al. (2015)	Gaudard et al. (2013); Hendel et al. (2015)
	Use of heat-resilient materials	Carnielo and Zinzi (2013); EEA (2019a); Wang et al. (2019)	Carnielo and Zinzi (2013); EEA (2019a); Wang et al. (2019)	Carnielo and Zinzi (2013); EEA (2019a); Wang et al. (2019)	Carnielo and Zinzi (2013); EEA (2019a); Wang et al. (2019)	Carnielo and Zinzi (2013); EEA (2019a); Wang et al. (2019)		
	Replacement of vulnerable infrastructure with resilient one	van Slobbe et al. (2016); Wang et al. (2019)	van Slobbe et al. (2016); Wang et al. (2019)					

Table SM13.16 | Reported adaptation limits for cities, settlements and key infrastructure in Europe (Figure 13.21)

Technical limits

Physical characteristics of the existing housing stock prevent high ventilation (Tillson et al., 2013).
There is limited efficacy of hard defences for high SLR (i.e., >1 m) and rapid rates of sea level rise (e.g., above 1 cm yr^{-1}) (see Box 13.1) (Umgiesser, 2020).
Natural ventilation is limited by safety, noise and air pollution concerns (Tillson et al., 2013; van Hooff et al., 2014; Mulville and Stravoravdis, 2016).
Too large sediment volumes are needed for beach nourishment (Galofré et al., 2016; Jiménez and Valdemoro, 2019).
Wet-bulb temperature below 2°C is needed for snowmaking (Spandre et al., 2016; Hartl et al., 2018).
Seawater cooling is feasible only for coastal plants (Behrens et al., 2017).
Management optimisation is not applicable to run-of-river hydropower plants (Gaudard et al., 2013).
Automation for flood discharge is not suitable for certain hydropower dams (EEA, 2020c).
Water temperature caps can reduce thermal power availability and cause blackouts (Eisenack, 2016).

Socioeconomic limits

Low flood probability prohibits the payoff of costly investments in home flood proofing (Poussin et al., 2015).
Energy poverty limits households' capacity to adapt to overheating (Sanchez-Guevara et al., 2019; Thomson et al., 2019).
High investments are needed for upgrading current drainage to new standards (EEA, 2020c).
High installation costs exist for applying flood-proofing measures beyond critical substations (EEA, 2020a).
There are no adaptation benefits from turning aerial transmission cables into underground cables in flood-prone areas (Sieber, 2013).

Environmental and regulatory limits

Minimum Energy Performance standards cover only residential air conditioners (Palkowski et al., 2019).
Space constraints exist on green infrastructure for flood management (Liu and Jensen, 2018).
There is limited or no availability of free areas in higher altitudes, and there are orographic constraints for expanding skiable corridors Campos Rodrigues et al. (2018).
There are limited water resources for increasing snowmaking (Spandre et al., 2016; Scott et al., 2019; Steiger et al., 2020).
An impossible inland shift of tourism and settlements exists due to coastal urbanisation or geomorphology (Toimil et al., 2018).
There is a lack of nearby alternative non-freshwater sources for plant cooling (Sieber, 2013).

Table SM13.17 | Present status of planned and implemented adaptation in cities, the energy sector, tourism, transport and industry in Europe (Table 13.1)

Sector	References
Cities	Reckien et al. (2015); EEA (2016b); Geneletti and Zardo (2016); Buurman et al. (2017); Davis et al. (2018); Gedikli and Balaban (2018); Reckien et al. (2018); CoM (2019); Pietrapertosa et al. (2019); Bertoldi et al. (2020)
Energy	EEA (2018); EEA (2019a); Gasho (2019)
Tourism	Gómez-Martín et al. (2014); Haanpää et al. (2015); Damm et al. (2017); Campos Rodrigues et al. (2018); Joye (2018); Landauer et al. (2018); Tirado et al. (2019)
Transport	Rotter et al. (2016); Battiston et al. (2017)
Industry and business	Averchenkova et al. (2016); Herrmann and Guenther (2017); Halkos et al. (2018); Schiemann and Sakhel (2018); Aguinaldo et al. (2019); D'Orazio and Popoyan (2019); CDSB (2020); de Bruin et al. (2020); Feridun and Güngör (2020); ECB (2021a); ECB (2021b)

SM13.6 Supplementary Material Supporting Section 13.7

Table SM13.18 | Literature sources used in the assessment of climate-sensitive infectious diseases (Figure 13.23)

Climate-sensitive infectious disease	References
Tick-borne encephalitis and borreliosis (Lyme)	Jaenson and Lindgren (2011); Rizzoli et al. (2011); Estrada-Pena et al. (2012); Jaenson et al. (2012); Medlock et al. (2013); Alkishe et al. (2017); Sykes and Makiello (2017); Tokarevich et al. (2017); Daniel et al. (2018); Medlock et al. (2018); Semenza and Suk (2018); Waits et al. (2018); Estrada-Pena and Fernandez-Ruiz (2020); Nah et al. (2020); Rogovskyy et al. (2020); Vandekerckhove et al. (2021)
West Nile virus	Semenza and Menne (2009); Medlock et al. (2015); Paz (2015); Proestos et al. (2015); Marini et al. (2016); Semenza et al. (2016); Vogels et al. (2017); Haussig et al. (2018); Vlaskamp et al. (2020); Marini et al. (2021); Rodriguez-Alarcon et al. (2021); Young et al. (2021)
Dengue, chikungunya, zika viruses	Caminade et al. (2012); Bouzid et al. (2014); Schaffner and Mathis (2014); Semenza et al. (2014); Kraemer et al. (2015); Cunze et al. (2016); Liu-Helmersson et al. (2016); Nsoesie et al. (2016); Rezza (2016); Shepard et al. (2016); Stanaway et al. (2016); Caminade et al. (2017); Tjaden et al. (2017); Mascarenhas et al. (2018); Medlock et al. (2018); Semenza and Suk (2018); Solimini et al. (2018); Tjaden et al. (2018); Liu-Helmersson et al. (2019); Messina et al. (2019); Metelmann et al. (2019); Ryan et al. (2019); Blagrove et al. (2020); Brugueras et al. (2020); Iwamura et al. (2020); Liu et al. (2020); Colon-Gonzalez et al. (2021); Oliveira et al. (2021); Ryan et al. (2021); Zeng et al. (2021)
Malaria	Caminade et al. (2014); Murdock et al. (2016); Piperaki and Daikos (2016); Hertig (2019); Fischer et al. (2020b); Karypidou et al. (2020)
Vibriosis	Baker-Austin et al. (2013); Escobar et al. (2015); Baker-Austin et al. (2017)

Table SM13.19 | Literature sources used in the assessment of feasibility and effectiveness of adaptation options for mortality, morbidity, exposure and stress from heat in Europe (Figure 13.24)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Heat	Behaviour-change measures	Khare et al. (2015); Hendel et al. (2017); Schuster et al. (2017)	Hendel et al. (2017)	Khare et al. (2015)	Khare et al. (2015)	Khare et al. (2015); Schuster et al. (2017)		
	Natural cooling	Alessandrini et al. (2019)		Alessandrini et al. (2019)		Alessandrini et al. (2019)		
	Building interventions	Åström et al. (2017); Taylor et al. (2018); Macintyre and Heaviside (2019); Murtagh et al. (2019)	Macintyre and Heaviside (2019)	Åström et al. (2017); Taylor et al. (2018); Macintyre and Heaviside (2019)		Åström et al. (2017); Macintyre and Heaviside (2019)		Fallmann et al. (2013)
	Green infrastructures	Richter (2016); Taylor et al. (2018); Rotzer et al. (2019); Venter et al. (2020)	Venter et al. (2020)	Richter (2016); Taylor et al. (2018); Rotzer et al. (2019); Venter et al. (2020)	Venter et al. (2020)	Taylor et al. (2018); Venter et al. (2020)	Rotzer et al. (2019); Venter et al. (2020)	Fallmann et al. (2013); Taylor et al. (2018); Rotzer et al. (2019); Venter et al. (2020)

		Effectiveness	Feasibility					
Impact type	Adaptation option		Economic	Technological	Institutional	Sociocultural	Ecological	Geophysical
Heat	Heat-proof land management	Fallmann et al. (2013); Åström et al. (2017); Montazeri et al. (2017)		Åström et al. (2017); Montazeri et al. (2017)	Donner et al. (2015); Åström et al. (2017)		Åström et al. (2017)	Fallmann et al. (2013); Donner et al. (2015); Montazeri et al. (2017)
	Heat health action plans	Gasparrini et al. (2015); Carmona et al. (2016); De'Donato et al. (2018)		Gasparrini et al. (2015); Carmona et al. (2016); De'Donato et al. (2018); Reischl et al. (2018); Morabito et al. (2019)	De'Donato et al. (2018); Reischl et al. (2018)	Gasparrini et al. (2015); De'Donato et al. (2018); Reischl et al. (2018); Morabito et al. (2019)	De'Donato et al. (2018); Casanueva et al. (2019); Morabito et al. (2019)	
	Bundle of options	Åström et al. (2017); Guo et al. (2018); Díaz et al. (2019)	Díaz et al. (2019)	Díaz et al. (2019)				Díaz et al. (2019)

SM13.7 Supplementary Material Supporting Section 13.8

Table SM13.20 | References supporting the examples of losses and damages to vulnerable livelihoods in Europe, differentiating for different categories of non-economic loss and damage (Table 13.2)

Example of losses and damages	Reference
Loss of livelihood, culture, health and well-being of the Sámi and the Nenets	Arctic Council (2013); Forbes et al. (2016); Hayashi (2017); Huntington et al. (2017); Mikhaylova (2018); Mustonen (2018); Inuit Circumpolar Council (2020); Feodoroff (2021)
Loss of key species in high-Arctic freshwater habitats, proliferation of introduced species and disruption of local food systems in Greenland, Finland, Sweden, northwest Russia and Scotland	Mustonen et al. (2018); Post et al. (2019); Frainer et al. (2020); Mustonen and Huusari (2020); Feodoroff (2021); Mustonen et al. (2021a); Mustonen et al. (2021b)
Warmer winters leading to loss of income from ice fishing and cultural heritage in Finland	Mustonen (2014); Mustonen and Huusari (2020)
Changes to marine food web resulting in loss of Indigenous knowledge and food insecurity in Greenland	Hayashi (2017); Pecl et al. (2017); Hayashi and Walls (2019); Inuit Circumpolar Council (2020)
Reduced yields on managed alpine grasslands decreasing the self-sufficiency of pastoral livestock farming in the Austrian, French and Swiss Alps	Brunner et al. (2019); Deléglise et al. (2019); Lavorel et al. (2019); Lavorel et al. (2020)
Reduced yields on semi-natural grasslands, compromising livestock feeding in winter, and ultimately decreasing viability of pastoralism in the Spanish Pyrenees	López-i-Gelats et al. (2016); Fernández-Giménez and Ritten (2020)
Retreating glaciers and changes in the landscape leading to loss of identity, culture and self-reliance in the Italian Alps (Alto Adige)	Jurt et al. (2015a); Jurt et al. (2015b)
Drought resulting in a reduction of provisioning (water) and regulating services (protection against floods) in the Western and Eastern Alps, Iberian Mountains and Dinaric Mountains	Leitinger et al. (2015); Mina et al. (2017); Schirpke et al. (2017); Strasser et al. (2019)
Increase of sea temperature leads to shifts in distribution of cold water species, reducing productivity at lower latitudes. Artisanal fisheries in Southern European coastal areas (Mediterranean) that rely on local, nearshore stocks can have difficulties to adapt	Lloret et al. (2018)

Table SM13.21 | References supporting Figure Box 13.2.1 'Cumulative impacts of climate and land-use change on reindeer herding as a traditional, semi-nomadic Sámi livelihood'

Indicator	References
Boundaries of reindeer herding areas in Sweden	Sámi Parliament in Sweden (2020)
Amount of snow	Ranasinghe et al. (2021)
Unstable ice conditions	Forbes et al. (2016); Mallory and Boyce (2018)
Frequent freeze–thaw cycles	Johansson et al. (2011); Hansen et al. (2014); Bokhorst et al. (2016); Rasmus et al. (2018)
Late snow melting during spring	Meredith et al. (2019)

Indicator	References
Heatwaves during summer	Skarin et al. (2010); Furberg et al. (2011); Löf (2013); Löf (2014); Meredith et al. (2019); Rosqvist et al. (2021)
Spread of new diseases	Omazic et al. (2019)
Insect harassment	Mallory and Boyce (2018); Tryland et al. (2019)
Psychological stress	Kaiser et al. (2010); Furberg et al. (2011); Stoor (2016)
Workload and costs	Furberg et al. (2011); Löf (2013); Löf (2014); Rosqvist et al. (2021)
Conflicts between herding communities and developers, authorities and members of local communities about the desirability of competing land uses	Lawrence (2014); Sehlin MacNeil (2015); Lawrence and Kløcker Larsen (2017); Persson et al. (2017); Beland Lindahl et al. (2018)
Self-determination and adaptive capacity	Brännlund and Axelsson (2011); Löf (2013); Brännström (2017); Allard (2018); Larsen and Raitio (2019)
Mining	Herrmann et al. (2014b); Eftestøl et al. (2019); Lawrence and Kløcker Larsen (2019); Österlin and Raitio (2020)
Hydropower	Össbo and Lantto (2011); Össbo (2018)
Forestry	Kivinen et al. (2012); Sandström et al. (2016); Fischer et al. (2020a)
Wind power	Skarin et al. (2015); Skarin and Alam (2017); Österlin and Raitio (2020)
Tourism	Nellemann et al. (2000); Skarin and Åhman (2014); Olsen (2016)

SM13.8 Supplementary Material Supporting Section 13.10

Table SM13.22 | Detected changes and attribution of climate-related impacts on land and in the ocean (Figure 13.27)

Assessment statement	Supporting references
Forest growth and production have been influenced by temperature and moisture conditions combined over recent centuries. The consequences of climate change have differed regionally, especially along the south-to-north axis.	Pretzsch et al. (2014); Reyer et al. (2014); Seidl et al. (2014); Gazol et al. (2015); Keenan et al. (2016); Reich et al. (2016); Tian et al. (2016); Alrahahleh et al. (2017); Ballantyne et al. (2017); Zlatanov et al. (2017); Humphrey et al. (2018); Marqués et al. (2018); Stocker et al. (2018); Vitali et al. (2018); Carnicer et al. (2019a); Ciais et al. (2019); Green et al. (2019); Yuan et al. (2019); Brodribb et al. (2020)
Tundra vegetation growth rate and shrub height have been accelerated by climate change.	Belonovskaya et al. (2016); Martin et al. (2017)
Drought consequences in the Mediterranean region have shown a significant increase in adverse effects, and outside the southern region the effects of drought have varied considerably.	Fantappié et al. (2011); Giuntoli et al. (2013); Yigini and Panagos (2016); Potopová et al. (2017); Stagge et al. (2017); Samaniego et al. (2018); García-Herrera et al. (2019); Spinoni et al. (2019); Zhou et al. (2019).
Crops have decreased due to temperature-related regional changes with variable regional impact in Europe, and optimal conditions of some crops have moved northward.	Garcia-Mozo et al. (2015); Long et al. (2016); Ceglar et al. (2017); Potopová et al. (2017); Zhao et al. (2017); Pérez-Domínguez and Fellmann (2018); Webber et al. (2018); Di Lena et al. (2019)
River floods have had increasingly damaging effects in Central Europe but have decreased in other regions.	Alfieri et al. (2015a); Polemio and Lonigro (2015); Ljungqvist et al. (2016); Blöschl et al. (2017); Kundzewicz et al. (2017); Paprotny et al. (2018); Berghuijs et al. (2019); Blöschl et al. (2019); Ganguli and Merz (2019); Lenderink et al. (2019); Umgiesser (2020)
Wildfire effects are jointly influenced by climate variables such as drought and temperature, but they are also highly influenced by management.	Moriondo et al. (2006); Moreno et al. (2014); Turco et al. (2014); Jolly et al. (2015); Tedim et al. (2015); Turco et al. (2016); de Rigo et al. (2017); Turco et al. (2017); Turco et al. (2018b); Michetti and Pinar (2019)
Marine heatwaves have induced mass mortality of sessile life forms, and such episodes have increased in frequency.	Garrabou et al. (2009); Munari (2011); Rivetti et al. (2014); Smale et al. (2015); Rubio-Portillo et al. (2016); Oliver et al. (2018); Darmaraki et al. (2019); Holbrook et al. (2019); Smale et al. (2019a)
Terrestrial species relocation rates towards higher latitude and altitude have increased.	Scherrer and Körner (2011); Oliver et al. (2015); Melero et al. (2016); Stephens et al. (2016); Wiens (2016); Bowler et al. (2017); Spooner et al. (2018); Lehikoinen et al. (2019a); van Klink et al. (2020a)
Marine species relocation from warm waters to previously colder, but now warming, waters has increased.	Fossheim et al. (2015); Hiddink et al. (2015); Montero Serra et al. (2015); van der Kooij et al. (2016); Chivers et al. (2017); García-Molinos et al. (2017); Cozzi et al. (2019); Vilà-Cabrera et al. (2019)
Coastal flood damaging effects have increased.	Haigh et al. (2011); Wahl et al. (2015); Malagon Santos et al. (2017); Garnier et al. (2018); Fernández-Montblanc et al. (2020); Umgiesser (2020)
Phenology changes were well documented in AR5, and subsequent studies have confirmed the trends.	Hassall et al. (2007); Visser et al. (2012); Karlsson (2014); Thackeray et al. (2016b); Mayor et al. (2017); Cohen et al. (2018b); Lehikoinen et al. (2019b, Ettinger et al. 2020); Menzel et al. 2020)

Assessment statement	Supporting references
Vector-borne diseases have expanded northward.	Daniel et al. (2003); Jaenson et al. (2012); Medlock et al. (2013); Jore et al. (2014); Tokarevich et al. (2017); Semenza and Suk (2018)
Winter tourism has experienced decreased potential due to reduced snow cover and reliability of natural snow, with severity of loss highest at low altitudes.	Falk (2015); Falk and Vanat (2016); Klein et al. (2016); Beniston et al. (2018); Falk and Lin (2018); Schöner et al. (2019). Rain-on-snow event frequency has increased (Beniston and Stoffel, 2016).
Damage from thaw of permafrost has been detected in a large range of societally important infrastructures, such as buildings and roads.	Stoffel et al. (2014); Porfiriev et al. (2017); Ravanel et al. (2017); Beniston et al. (2018); Duvillard et al. (2019)
Energy demand for cooling has increased and for heating has decreased due to increasing temperatures.	De Rosa et al. (2015); Spinoni et al. (2015); EEA (2017a policies and practices)
Macroeconomic damage for Europe has been detected.	Burke et al. (2015); Diffenbaugh and Burke (2019)
Shoreline erosion has been detected, but the literature is limited.	Castelle et al. (2018); Mentaschi et al. (2018)
Aquatic species relocation includes expansion northward, which in the southern region implies tropicalisation.	Zhang et al. (2017); Monchamp et al. (2018); Kärcher et al. (2019); van Klink et al. (2020a)
Heatwaves have induced mortality at increasing frequency and severity.	Shaposhnikov et al. (2015); Morabito et al. (2017); Vogel et al. (2019); Vicedo-Cabrera et al. (2021)
Ocean acidification combined with warming affects several aspects of marine commercial gain.	Lacoue-Labarthe et al. (2016); Fernandes et al. (2017)
Fisheries specimen size distribution has changed. The frequency of small specimen size has increased in southern regions of European waters.	Fortibuoni et al. (2015); Gamito et al. (2015); Teixeira et al. (2016); Ding et al. (2017); Ojea et al. (2017); Free et al. (2019); Stecf (2019)
Miscellaneous effects with *limited evidence* are not included in Figure 13.29. Several isolated examples of effects that can be attributed to climate change have been adequately reported.	For example, increase in groundwater heavy metal contamination from fractured aquifers, Bondu et al. (2016); effects in livestock, Handisyde et al. (2017) and Rojas-Downing et al. (2017); pathogen sensitivity, McIntyre et al. (2017) and Moretti et al. (2019); and heat damage to railway tracks, Ferranti et al. (2018)

Note:

This assessment is based on peer-reviewed literature in this chapter that reported observed evidence with at least 90% significance and usually with 95% significance or more.

Table SM13.23 | References for assessment of macroeconomic damages and gains for selected climate risks, measured by GDP and welfare for 1.5°C and 3°C GWL relative to no additional warming (Figure 13.33)

Risks	GWL	References
Change in agricultural yields	1.5°C	Szewczyk et al. (2018); Bosello et al. (2020); Szewczyk et al. (2020)
	3°C	Roson and Sartori (2016); Aaheim et al. (2017)[a]; Szewczyk et al. (2018); Dellink et al. (2019)[a]; Bosello et al. (2020); Szewczyk et al. (2020)
Change in labour productivity	1.5°C	Szewczyk et al. (2018); Bosello et al. (2020); Knittel et al. (2020)[b]; Orlov et al. (2020)[a]
	3°C	Roson and Sartori (2016); Takakura et al. (2017)[a]; Szewczyk et al. (2018); Bosello et al. (2020); Orlov et al. (2020)[a]; García-León et al. (2021)
Change in energy demand	1.5°C	Szewczyk et al. (2018); Bosello et al. (2020)
	3°C	Szewczyk et al. (2018); Dellink et al. (2019)[a]; Bosello et al. (2020)
Change in mortality due to heat	1.5°C	Szewczyk et al. (2018); Szewczyk et al. (2020)
	3°C	Roson and Sartori (2016); Aaheim et al. (2017)[a]; Szewczyk et al. (2018); Dellink et al. (2019); Szewczyk et al. (2020)
Damage to economic sectors from water scarcity and drought	1.5°C	Faust et al. (2015)[b]; Koopman et al. (2017)[b]; Szewczyk et al. (2020); Teotónio et al. (2020)[b]
	3°C	Szewczyk et al. (2020); Teotónio et al. (2020)[b]
Change in energy supply	1.5°C	Bosello et al. (2020); Szewczyk et al. (2020)
	3°C	Aaheim et al. (2017)[a]; Bosello et al. (2020); Szewczyk et al. (2020)
Damage to infrastructure from coastal flooding	1.5°C	Pycroft et al. (2016); Szewczyk et al. (2018); Bosello et al. (2020); Szewczyk et al. (2020)
	3°C	Pycroft et al. (2016); Roson and Sartori (2016); Aaheim et al. (2017); Szewczyk et al. (2018); Dellink et al. (2019)[a]; Bosello et al. (2020); Parrado et al. (2020)[a]; Szewczyk et al. (2020)
Damage to infrastructure from inland flooding	1.5°C	Dottori et al. (2018)[a]; Szewczyk et al. (2018); Koks et al. (2019); Bosello et al. (2020); Parrado et al. (2020)[a]; Szewczyk et al. (2020)
	3°C	Aaheim et al. (2017); Dottori et al. (2018)[a]; Szewczyk et al. (2018); Dellink et al. (2019); Koks et al. (2019); Bosello et al. (2020); Szewczyk et al. (2020)

Notes:

(a) Only larger European sub-regions are covered.

(b) Single country or subset of countries.

SM13.9 Supplementary Material Supporting the Feasibility and Effectiveness Assessment

Background

The assessment aimed to provide an overview of the current knowledge of the feasibility and effectiveness (F&E) of selected adaptation options for key climate risks in Europe, and inform the design of the illustrative adaptation pathways in Section 13.10.2 (see SM13.11). Feasibility is understood as the potential for an adaptation option to be implemented. Feasibility depends on geophysical, environmental–ecological, technological, economic, sociocultural and institutional factors that enable or constrain the implementation. Effectiveness refers to the potential the option has to reduce risk compared with a baseline (see AR6-WGII Annex II).

Figure SM13.1 presents the main steps taken in the F&E assessment. The evidence presented in Figures 13.6, 13.14, 13.20 and 13.24 is the result of the available scientific evidence presented in the Supplementary Material (Tables SM13.1, SM13.5, SM13.15, SM13.19) and expert interpretation of these data. The approach was largely similar to the IPCC AR6 Special Report: Global Warming of 1.5˚C (Chapter 4, de Coninck et al., 2018), and is further detailed in Singh et al. (2020).

Scientific articles were collected from a range of sources including the Global Adaptation Mapping Initiative (Berrang-Ford et al., 2021), focused literature searches by the author team, including contributing authors, and references suggested by reviewers. The assessment focused on those studies that empirically assessed (i.e., using case studies, models, experiments) the feasibility and effectiveness of adaptation options, thereby excluding conceptual and opinion articles. Only articles that explicitly considered measures to adapt to the observed impacts or projected risks of climate change were included to ensure conceptual consistency of the assessment, as is common in most systematic assessments on climate-change adaptation (Berrang-Ford et al., 2015). Moreover, articles were only included when they reported a clear link between the adaptation option and one or several of the feasibility and effectiveness assessment criteria. Articles listing general enabling and constraining factors to adaptation within a sector in general, for example, were not included in the F&E assessment. Grey literature and articles not in the English language were not included due to time and resource constraints. These articles may have created a bias in the datasets used for the assessment.

Detailed methods of the assessment approach and calculation of the scores for individual indicators and aggregation to the six feasibility dimensions can be found in Singh et al. (2020). The results visualised in the figures is the combination of scientific evidence and discussions among experts in the author team. Contributing authors were invited to participate when expertise within the Lead Author team was limited.

SM13.10 Supplementary Material Supporting the Key Risks and Burning Embers Assessments

The detailed methodology for the key risk assessment is described in Chapter 16. Lead and Contributing Authors in Chapter 13 have been assigned to assess the key risks literature based on their expertise and contributions to the chapter. Data were extracted from the references listed in Table SM13.22 and entered in five different spreadsheets (two spreadsheets for key risk 1 and one for each of the other key risks): reference, IPCC sub-regions, RCPs or any other corresponding climate scenarios, time periods, warming (GSAT) from pre-industrial levels derived according to the common climate dimensions (see Cross Chapter Box CLIMATE in Chapter 1), climate-impact drivers (Ranasinghe et al., 2021), SSPs (if available), climate models and type of simulations, impact models, sector(s) affected, risk metric, risk consequences and comments.

Following the data extraction, the key risk teams participated in expert elicitation workshops to reach consensus on the risk and temperature transition levels to feed into the construction of the burning ember diagrams in Figures 13.29–13.32 (see Zommers et al., 2020). The methodology is provided in Section SM13.11 and was slightly adapted for the assessments in this chapter. Results are summarised in Tables SM13.25–SM13.31.

General workflow for assessing effectiveness and feasibility of adaptation options

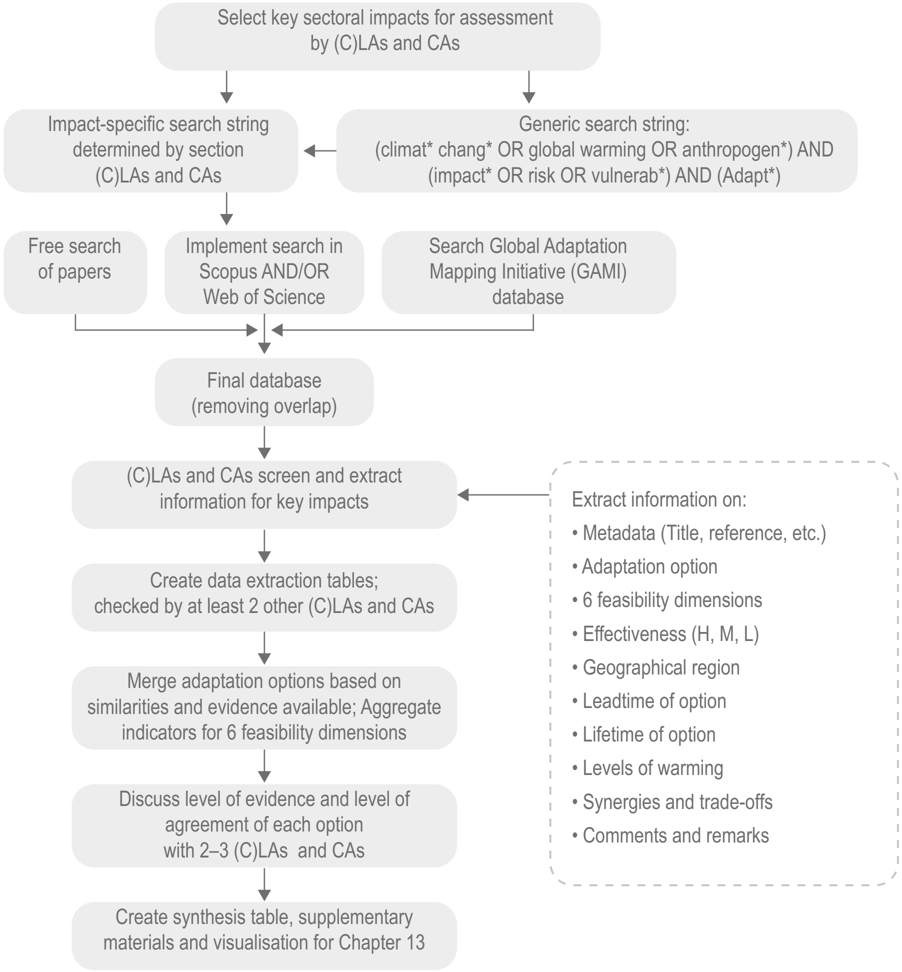

Figure SM13.1 | General workflow for assessing effectiveness and feasibility of adaptation options

Table SM13.24 | List of references supporting the assessment of the key risks (Figure 13.28)

Key Risk	References
KR1: Risks of human mortality and heat stress, and of ecosystems disruptions, due to heat extremes and increase in average temperatures	
Human health	Frolov et al. (2014); Jenkins et al. (2014b); Barbosa et al. (2015); Åström et al. (2017); Forzieri et al. (2017); Gasparrini et al. (2017); Hamdy et al. (2017); Hunt et al. (2017); Kendrovski et al. (2017); Mora et al. (2017); Cellura et al. (2018); Forzieri et al. (2018); Guo et al. (2018); Heracleous and Michael (2018); Arnell et al. (2019); Díaz et al. (2019); Revich et al. (2019); Rohat et al. (2019); Casanueva et al. (2020); Lee et al. (2020); Vanos et al. (2020); Ebi et al. (2021)
Marine ecosystems	Roebeling et al. (2013); Albouy et al. (2014); Brodie et al. (2014); Carstensen et al. (2014); Frolov et al. (2014); Herrmann et al. (2014a); Maugendre et al. (2014); Hennige et al. (2015); Serra et al. (2015); Wall et al. (2015); Cheung et al. (2016); García Molinos et al. (2016); Holt et al. (2016); Krumhansl et al. (2016); Lam et al. (2016); Ragazzola et al. (2016); Spencer et al. (2016); Stiasny et al. (2016); Thackeray et al. (2016b); Fernandes et al. (2017); Galli et al. (2017); Narita and Rehdanz (2017); Semenza et al. (2017); Thomsen et al. (2017); Townhill et al. (2017); Wang et al. (2017b); Benedetti et al. (2018); Corrales et al. (2018); Gao et al. (2018); Jokinen et al. (2018); Mangi et al. (2018); Riebesell et al. (2018); Sswat et al. (2018b); van der Spek (2018); Wang et al. (2018); Chefaoui et al. (2019); de la Hoz et al. (2019); Durant et al. (2019); Edelgeriev (2019); Herrera et al. (2019); Lotze et al. (2019b); Moullec et al. (2019); Petrik et al. (2019); Richon et al. (2019); Roggatz et al. (2019); Spivak et al. (2019); Bryndum-Buchholz et al. (2020); Clark et al. (2020); Maltby et al. (2020); Xi et al. (2021)
Terrestrial ecosystems	Gallego-Sala et al. (2010); Perch-Nielsen et al. (2010); Dury et al. (2011); San-Miguel-Ayanz et al. (2012); Filipe et al. (2013); Matzarakis et al. (2013); Steiger and Stötter (2013); Bedia et al. (2014); Frolov et al. (2014); Markovic et al. (2014); Matzarakis et al. (2014); Oliver et al. (2015); Urban (2015); Wu et al. (2015a); Brambilla et al. (2016); Grillakis et al. (2016); Polce et al. (2016); Scott et al. (2016); Thackeray et al. (2016b); Camia et al. (2017); EEA (2017a); Pecl et al. (2017); Sáenz-Romero et al. (2017); Vazquez et al. (2017); Vermaat et al. (2017); Dyderski et al. (2018); Ceglar et al. (2019); Ferretto et al. (2019); Jakoby et al. (2019a); Lotze et al. (2019b); Berberoglu et al. (2020); Feyen et al. (2020); Gianinetto et al. (2020); Qiu et al. (2020); Wamelink et al. (2020); Urvois et al. (2021); Xi et al. (2021)

Key Risk	References
KR2: Risk of losses in crop production, due to compound heat and dry conditions, and extreme weather	
	Caffarra et al. (2012); Sutton et al. (2013); Deryng et al. (2014); Donatelli et al. (2015); Reidsma et al. (2015); Bird et al. (2016); Castellanos-Frias et al. (2016); Knox et al. (2016); Webber et al. (2016); Diogo et al. (2017); Holman et al. (2017); Nielsen et al. (2017); Popp et al. (2017); Siebert et al. (2017); Williges et al. (2017); Ben-Ari et al. (2018); Parent et al. (2018 with an appropriate use of the genetic variability of flowering time); Ruiz-Ramos et al. (2018); Szewczyk et al. (2018); Webber et al. (2018); Ceglar et al. (2019); Chen et al. (2019); EEA (2019b); Grillakis (2019); Moretti et al. (2019); Papadimitriou et al. (2019); Toreti et al. (2019); Feyen et al. (2020); Jäger et al. (2020); Huttunen et al. (2021); Pedde et al. (2021)
KR3: Risk of water scarcity to multiple interconnected sectors	
	Blauhut et al. (2015); Collet et al. (2015); Kebede et al. (2015); Papadaskalopoulou et al. (2015b); Blauhut et al. (2016); Gain et al. (2016); Gampe et al. (2016); Schleussner et al. (2016); Stahl et al. (2016); Koopman et al. (2017); van Vuuren et al. (2017); Byers et al. (2018); Greve et al. (2018); Iglesias et al. (2018); Manouseli et al. (2018); Naumann et al. (2018); Tobin et al. (2018b); Arnell et al. (2019); Garnier and Holman (2019); Harrison et al. (2019); Koutroulis et al. (2019); Morote et al. (2019); Papadimitriou et al. (2019); Bisselink et al. (2020); Cammalleri et al. (2020); Teotónio et al. (2020); Kebede et al. (2021); Naumann et al. (2021)
KR4: Risks to people, economies and infrastructures due to coastal and inland flood hazards	
Coastal flooding	Ciscar et al. (2014); Marzeion and Levermann (2014); Clark et al. (2016); Pycroft et al. (2016); Reimann et al. (2018); Vousdoukas et al. (2018); Arnell et al. (2019); Harrison et al. (2019); Vousdoukas et al. (2020); Haasnoot et al. (2021)
Inland flooding	Jongman et al. (2014); Alfieri et al. (2015b); Alfieri et al. (2016a); Alfieri et al. (2016b); Alfieri et al. (2017); Alfieri et al. (2018); Ciscar et al. (2018); Dottori et al. (2018); Paprotny et al. (2018); Arnell et al. (2019); Harrison et al. (2019); Papadimitriou et al. (2019); Dottori et al. (2020); Hosseinzadehtalaei et al. (2020); Lange et al. (2020); Merz et al. (2021)

Table SM13.25 | Transition and confidence levels for the risks of human mortality and heat stress due to heat extremes and increase in average temperature (Figures 13.28, 13.29)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
Risk level with present to medium adaptation, including SSP2–SSP4			
Undetectable to moderate risk	0.7–1.0	*high*	The range and confidence are supported by evidence from the detection and attribution assessment (Figure 13.27; Table SM13.1; Vicedo-Cabrera et al., 2021). The range reflects warming between 1995 and 2014 as reported in WGI Cross-Chapter Box 2.3 in Chapter 2. Furthermore, the climate-impact drivers (both mean air temperature and extremes) emerged already in the historical period with *medium confidence* (WGI Figure 12.7). Detected risk to date (selected from the D&A assessment in Section 13.10.1): Shaposhnikov et al. (2015); Morabito et al. (2017); Vogel et al. (2019); Vicedo-Cabrera et al. (2021)
Moderate to high risk	1.6–2.2	*high*	The magnitude of consequences attributed to a number of risk metrics, such as mortality and population exposure to heat extremes, all increase beyond 1.5°C GWL. Naumann et al. (2020a) show an increase already at 1.5°C GWL, but there is less evidence and consensus that a transition happens before or at 1.5°C GWL. The risk also increases less rapidly for every indicator, or at least there is little consensus in the literature. It is higher and more likely in southern regions but not everywhere. Magnitude of risk consequences reported in the literature to support this transition: – Excess mortality attributable to climate change: 1.5–1.67% (NEU, WCE, SEU) (Gasparrini et al., 2017) – Proportion of the European population at risk of heat stress: 161 million (Rohat et al., 2019) in EU-27 plus the UK – Additional attributable deaths in Europe: 30,867 (with no climate change: 17,384) – Increase in heatwave excess deaths in SEU, WCE and NEU with the highest increase in NEU (Guo et al., 2018) – People annually exposed to a once-in-50-year heatwave: 176 million (present value: 9.6 million) and heat fatalities per year: 52,182 (present value: 2752) (Naumann et al., 2020a) Literature supporting this transition: Forzieri et al. (2017); Gasparrini et al. (2017); Hunt et al. (2017); Kendrovski et al. (2017); Guo et al. (2018); Rohat et al. (2019); Lee et al. (2020); Naumann et al. (2020b)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
High to very high risk	2.9–3.5	*medium*	Some studies point to a transition at higher levels and others at lower levels; however, the risk becomes more persistent and increases in every region as well as its likelihood. The ability to adapt is not completely excluded, but assuming current adaptation conditions or SSP2/SSP4, very high risk will be realised under 3°C GWL. Magnitude of risk consequences reported in the literature to support this transition: At 3°C GWL: – Proportion of the European population at risk of heat stress compared with the reference period 1982–2005 (in parentheses): 216 million / 48.4% (2.1 million / 0.4%) (Rohat et al., 2019) – Extreme-heat-related deaths per 10 million inhabitants (1981–2010): 2817 (54.7) (Forzieri et al., 2017) – Heat fatalities per year: 90 thousand (Naumann et al., 2020a) – Extreme-heat-related deaths per 10 million inhabitants: 2816.9 in EU-27 plus the UK (Forzieri et al., 2017) At 3.5–4°C GWL: – Attributable death: 117,333 (with no climate change: 16,303) (Kendrovski et al., 2017) – Increase in heatwave-related deaths compared with the present warming levels: 200–280% (highest increase in NEU) Literature supporting this transition: Forzieri et al. (2017); Kendrovski et al. (2017); Rohat et al. (2019); Casanueva et al. (2020); Naumann et al. (2020b)
Risk level with high adaptation, including SSP1			
Undetectable to moderate risk	0.7–1.0	*high*	The range and confidence level are supported by evidence from the detection and attribution assessment (Figure 13.29; Table SM13.1; Vicedo-Cabrera et al., 2021). The ranges reflect warming between 1995 and 2014 as reported in WGI Cross-Chapter Box 2.3 in Chapter 2. Furthermore, the climate-impact drivers (both mean air temperature and extremes) emerged already in the historical period with *medium confidence* (Figure 12.7; Ranasinghe et al., 2021). Detected risk to date (from D&A assessment in Section 13.10.1): Shaposhnikov et al. (2015); Morabito et al. (2017); Vogel et al. (2019); Vicedo-Cabrera et al. (2021); additional evidence from the F&E assessment is given in Tables SM13.5.3 and SM13.6.2.
Moderate to high risk	2.5–3.8	*medium*	This transition is based on a body of literature which considers the adaptation needed to maintain the number of deaths at the current level or SSP1 conditions. It confirms that the mortality rates are smaller and the number of people at risk of heat stress are much fewer than those with only present to moderate adaptation (Åström et al., 2017; Guo et al., 2018; Díaz et al., 2019; Rohat et al., 2019). For example, Åström et al. (2017) calculate the rate of adaptation needed at around 2°C GWL to maintain the number of deaths at the present level and found this rate to be over 75%. Various caveats concern the assumptions of full acclimatisation above 3°C and the existence of possible physiological limits (Vanos et al., 2020). Ebi (2021) have found that the burning ember for heat-related mortality and morbidity with high adaptation (e.g., SSP1) has a transition between 2 and 3°C GWL. Considering that this is a global study and taking into account the evidence on high adaptation, we conclude that the transition level is somewhere above 2°C but below 4°C (Åström et al., 2017; Guo et al., 2018; Díaz et al., 2019). Additional evidence from the F&E assessment is given in Tables SM13.5.3 and SM13.6.2.
High to very high risk	Does not reach this level	n.a.	There is little evidence that the risk will reach this level assuming full adaptation because the adaptation potential is still higher in high-adaptation scenarios in several regions (NEU), e.g., and in agreement with, the burning embers in Ebi et al. (2021). We concluded that under a high-adaptation scenario, the risks do not reach this threshold.

Table SM13.26 | Transition and confidence levels for the risks of marine ecosystems disruptions due to heat extremes and increase in average temperatures (Figure 13.28)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the risk-level transition	Explanation and references
Undetectable to moderate	0.9–1.7	*medium*	A comprehensive summarising assessment across all impacts and risks on or for marine systems is impaired by the uneven distribution of available information on their levels and development driven by RCP scenarios at 1.7°C, 2.5°C and above 4°C GWL, making the determination of transitions challenging. The transition from undetectable to moderate starts around or less than 1°C to 1.7°C with *medium confidence*. Detected to date (selected from the D&A assessment in Section 13.10.1): – Marine heatwaves that have increased in frequency and induced mass mortality (Garrabou et al., 2009; Munari, 2011; Rivetti et al., 2014; Rubio-Portillo et al., 2016; Smale et al., 2019b) – Marine species relocation (Fossheim et al., 2015; Hiddink et al., 2015; Montero Serra et al., 2015; van der Kooij et al., 2016; Chivers et al., 2017; Cozzi et al., 2019) – Detected changes in range expansion (Birchenough et al., 2015), species distribution and species phenologies leading to a change from plankton communities (Burrows et al., 2019) to subtropicalisation of European pelagic fish communities (Montero Serra et al., 2015) – Change in size of catch of fisheries (Fortibuoni et al., 2015; Gamito et al., 2015; Teixeira et al., 2016; Ding et al., 2017; Ojea et al., 2017; Free et al., 2019; Stecf, 2019) Projected risk (further information in Figure 13.11): At 1.7°C GWL: – Increasing risks across systems (from habitat losses to biodiversity and ecosystem services); while observed impacts were or are most severe first in the Mediterranean, at this GWL risks projected to extend to transitional waters – 13% diversity losses YB19 (25–40% loss in animal biomass) (Bryndum-Buchholz et al., 2019; Lotze et al., 2019a) – 20% loss coastal wetland, 7% loss in ecosystem value (Roebeling et al., 2013) – 60% habitat reduction for fish in the Mediterranean (Clark et al., 2020), impacting commercially important fish (e.g., anchovy) (Raybaud et al., 2017) – Loss of 20–40% change in catch potential of shellfish and 20% in fish (Lam et al., 2016; Fernandes et al., 2017)
Moderate to high	2–2.2	*low*	Note: Confidence level is *low* because there is a distinct gap in information on risk development for levels between 1.7 and 2.5°C GWL. At 2°C GWL: – Increase in area suitable for viruses (Semenza et al., 2017) – Increase in likelihood of marine heatwaves (Frölicher et al., 2018)
High to very high	2.5–3	*high*	At 2.5°C GWL: – Strong risks across shallow-water ecosystems due to the combined warming and SLR: projected 28% loss in coastal wetlands and 10% ecosystem value (Roebeling et al., 2013); regionally up to 80% loss in wetland (Spencer et al., 2016) – Drowning of intertidal flats in TEUS (van der Spek, 2018) – Changes in species dominance (Moullec et al., 2019) – Diversity loss of 20% in TEUS and 40% in NEUS (García Molinos et al., 2016) – Losses in shellfish biomass in TEUS increasing from 40 to 50% locally and up to 80% in response to warming, and resulting habitat loss with significant economic losses (Fernandes et al., 2017; Galli et al., 2017; Mangi et al., 2018), 30% loss of fin fish (Cheung et al., 2016; Lam et al., 2016) and loss of habitat for economically important shellfish in the SEUS (Mangi et al., 2018) – Decrease in potential catch of cod and other economically important species (Maltby et al., 2020); needs changing in consumer behaviour and fishing At 3°C GWL: – Loss of important habitat formers in coastal systems (Brodie et al., 2014) – Decrease in primary productivity (Maugendre et al., 2014) Above 4°C GWL – 1.5 to 50% losses in macroinvertebrates, – Doubling of mortality of larva of economically important species, – 30–50% diversity losses, – 25–70% lower marine animal biomass – shellfish production collapses, – loss of habitat of species important for climate change mitigation, such as wetlands, limits their contribution

Table SM13.27 | Transition and confidence levels for the risks of terrestrial ecosystems disruptions due to heat extremes and increase in average temperatures (Figure 13.28)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
Undetectable to moderate risk	1–1.5	*medium*	There is increasing evidence across systems, but impacts are not yet considered severe and widespread based on the evidence. Detected to date (selected from the D&A assessment in Section 13.10.1): – Forest growth and production has been impacted by temperature and moisture over the past century (Pretzsch et al., 2014; Seidl et al., 2014; Gazol et al., 2015; Tian et al., 2016; Alrahahleh et al., 2017; Zlatanov et al., 2017; Marqués et al., 2018; Carnicer et al., 2019a; Ciais et al., 2019; Yuan et al., 2019; Brodribb et al., 2020). – Compound events of heat and drought have impacted forest growth with legacy effects into the next year (Schuldt et al., 2020). – Tundra vegetation shrub encroachment has been accelerated by climate change (Belonovskaya et al., 2016; Martin et al., 2017). – Drought consequences in the Mediterranean region (Fantappié et al., 2011; Stagge et al., 2017; García-Herrera et al., 2019). – Terrestrial species relocation towards higher latitude and altitude have increased in rate (Scherrer and Körner, 2011; Oliver et al., 2015; Melero et al., 2016; Stephens et al., 2016; Wiens, 2016; Bowler et al., 2017; Spooner et al., 2018; Lehikoinen et al., 2019a; van Klink et al., 2020b). – Range shifts have altered boreal and alpine tundra (Elmhagen et al., 2015; Post et al., 2019; Mekonnen et al., 2021) and greened polar deserts (Myers-Smith et al., 2020). – Climate-induced biodiversity declines have been detected in thermosensitive groups (Hellmann et al., 2016; Habel et al., 2019; Harris et al., 2019; Crossley et al., 2020; Soroye et al., 2020) including many freshwater plants, molluscs, flying insects, amphibians, reptiles, birds and fishes (Myers et al., 2017; Jarić et al., 2019; Kärcher et al., 2019; Seibold et al., 2019; van Strien et al., 2019; van Klink et al., 2020a). – Phenology changes (Hassall et al., 2007; Visser et al., 2012; Karlsson, 2014; Szabó et al., 2016; Thackeray et al., 2016b; Mayor et al., 2017; Asse et al., 2018; Cohen et al., 2018b; Bobretsov et al., 2019; Peaucelle et al., 2019; Menzel et al., 2020; Rosbakh et al., 2021). Warming between 1.5°C and 2°C GWL is projected to increase the impact including: – Expansion of the subtropical vegetation in SEU (Feyen et al., 2020) and large-scale threats for forest areas WCE (Dyderski et al., 2018) – Loss of 50% of the tundra biome in NEU and 40% WCE alpine regions (Feyen et al., 2020) – Loss in peatland area in NEU (Qiu et al., 2020) – Some losses in grassland in WCE (Vermaat et al., 2017) – Extinction risk of 5% of species in Europe (Urban (2015) – Loss of 6% of common and 77% of rare freshwater species extinction (Markovic et al., 2014) – 50% of protected area loss of mollusc and freshwater fish (Markovic et al., 2014) – Increasing changes in phenology, creating consumer primary producer mismatch (Thackeray et al., 2016a) – Habitat loss for pollinators in NEU (Rasmont et al., 2015), increasing risk to sensitive pollinators; uncertain net impacts on the pollination service – Increases in burned area (Wu et al., 2015a) – Increase in soil erosion by 8% in SEU (Berberoglu et al., 2020), increase in rainfall erosion especially in in NEU (Panagos et al., 2017) and increase in soil loss from fire (Pastor et al., 2019b); however, soil erosion is made of many different components (e.g., precipitation, soil type, topography, land use and land management, and hence human impacts and vegetation responses to climate change are difficult to separate from climatic effects – Autonomous adaptation allowing species to shift ranges (if protected areas are sufficiently large and corridors are available, freshwater bodies are connected and, for plants, if soil types and hydrology are appropriate); opportunity for adaptation and reversibility which currently reduces the risk
Moderate to high risk	2–2.5	*medium*	The risk is increasing for a larger number of ecosystems, and the extent of loss and impact is becoming irreversible: – Increase in wildfire risk in the SEU (Bedia et al., 2014) and increase in burnt area (Camia (2017) – Expansion of temperate flora in 30% of NEU, 60% of tundra NEU and 50% of alpine tundra (Feyen et al., 2020) – 50% carbon loss in blanket bogs NEU (Ferretto et al., 2019) – 12% loss of meadows (Wamelink et al., 2020) – Increase in pests, such a bark beetle, in WCE (Jakoby et al., 2019b) – Increased extinction risk (Warren et al., 2018) Above 2.5°C GWL: – 70% range contraction in birds in the Alps (Brambilla et al., 2016) – Increase in threatened forest area by 46% in WCE (Dyderski et al., 2018) – Up to doubling in burned area (Wu et al., 2015a; Camia, 2017; EEA, 2017b)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
High to very high risk	3.3–3.8	*high*	The magnitude of several indicators (including losses) are projected to increase very strongly above 3°C GWL: – NEU and SEU tundra nearly completely lost, 70% of alpine tundra (Feyen et al., 2020) – Strong expansion of temperate flora into NEU and subtropical flora into WCE (Feyen et al., 2020) – Peat turning into carbon source (Qiu et al., 2020) – 8–16% of species at risk of extinction (Urban, 2015; Warren et al., 2018) Above 3.5°C GWL: – Large expansion of tree pest species in MED and WCE (Urvois et al., 2021) – 25% increase in soil erosion in SEU (Berberoglu et al., 2020) – Large habitat losses and diversity loss of 10–48% of pollinators NEU (Rasmont et al., 2015) – Species risk of extinction of 16% (Urban (2015) – Strong increases of the burned areas in Europe (Wu et al., 2015a; EEA, 2017b) – WCE threatened forest area 59% (Dyderski et al., 2018)

Table SM13.28 | Transition and confidence levels for risk of losses in crop production due to compound heat and dry conditions, and extreme weather (Figures 13.28, 13.30)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
Risk level with low adaptation			
Undetectable to moderate risk	0.8–1.1	*medium*	This transition is supported by the D&A assessment in Section 13.10.1 and references therein. This transition is placed around the 1°C GWL range. The impacts have been mainly attributed in the case of the extremes, where events in years such as 2010, 2016 and 2018 indicate the future on agricultural yields given the expected higher frequency and severity of these events. The average losses across Europe are not currently sufficiently large for risk to be widespread. At 1.5°C–1.7°C GWL: – Likelihood of compound events which has led to recent large wheat losses are projected to become 12% more frequent, challenging farming systems and yield forecasting systems (Ben-Ari et al., 2018) – Maize yield losses across Europe of 10–25% (Deryng et al., 2014; Webber et al., 2018; Feyen et al., 2020), though strongest in SEU – Wheat productivity not impacted at 1.7°C GWL (Webber et al., 2018) – Changes in SEU as growing regions shift northward for melons (Bisbis et al., 2019), tomatoes and grapevines reaching NEU and EEU (Hannah et al., 2013; Litskas et al., 2019) – Beginning of abandonment of agricultural land in SEU (Holman et al., 2017) – Warming that causes range expansion and alters host pathogen association of pests, diseases and weeds (Caffarra et al., 2012; Pushnya and Shirinyan, 2015; Latchininsky, 2017) – Regionally predicted reduction in rainfall which can lead to carryover of herbicides (Karkanis et al., 2018)
Moderate to high risk	2.5–3	*medium*	At 2°C GWL: – 30–50% yield reduction of rain-fed maize in SEU (EEA, 2019b; Feyen et al., 2020) – Increase in agricultural droughts (Toreti et al., 2019) – Locally strong changes in yield in arable systems (Diogo et al., 2017) – Increase in toxins in maize in SEU and emergence in WCE (Moretti et al., 2019) – 15% yield loss for sugar beet in rain-fed system in SEU (EEA, 2019b) At 2.7°C GWL: – Impacts becoming more widespread as agroclimatic zones move (Ceglar et al., 2019), though there are still regional gains in parts of WCE and NEU (Szewczyk et al., 2018) – Increasing uncertainty of the impact on wheat and rapeseed yields in SEU and WCE (Donatelli et al., 2015) – 108% increase in expanse of damaging weed for winter crops (Castellanos-Frias et al., 2016) – Heat stress on wheat in EEU (Ceglar et al., 2019) – Negative impact on pollinators resulting in reduced visits of bees (Nielsen et al., 2017) (see also Section 13.3.1.3) – Between 2.5°C–2.7°C and 3°C GWL, more crops being affected, though there is uncertainty of the extent of potential losses with some gains possible

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
High to very high risk	3.8–4	*low*	At 3°C–4°C GWL: Most of the evidence focuses on temperatures below 3°C GWL and above 4°C GWL with *limited evidence* of impacts between 2.7 and 4°C GWL. Given that only a very small number of papers are available at these warming levels, the confidence level is *low*.
			At 3.3°C GWL: – Loss of tomato production in parts of SEU (Bird et al., 2016) – 170% increase in expanse of damaging weed for winter crops (Castellanos-Frias et al., 2016) – NEU becoming a suitable climate for the wheat pest *Lolium rigidum* (Castellanos-Frias et al., 2016) At 4°C GWL and beyond: – Constant drought conditions similar to spring/summer 2018 (Ben-Ari et al., 2018) – Maize yield losses across Europe of 50–100% (Deryng et al., 2014; Webber et al., 2018; Feyen et al., 2020) – Losses in spring wheat (Deryng et al., 2014), though gains projected for EEU – Reduction in grassland biomass and start seeing losses in NEU (Jäger et al., 2020) – Increasing losses in agricultural yield SEU and WCE (Szewczyk et al., 2018) – Increased asynchrony between the larvae-resistant growth stages of grapevine and larvae occurrence (Caffarra et al., 2012)
Risk level with high adaptation			
Undetectable to moderate risk	0.8–1.1	*medium*	This transition is supported by the D&A assessment in Section 13.10.1 and the references therein (Table SM13.1), and is placed around the 1°C GWL range. High levels of implementation of multiple adaptation options are assumed for this high-adaptation burning ember. Agricultural production risks can be reduced through irrigation given the availability water resources and suitable infrastructure (Siebert et al., 2017; Ruiz-Ramos et al., 2018; Feyen et al., 2020). The ability to adapt through irrigation is constrained as increasing water is needed to reduce impacts of heat and reduce yield losses with higher temperature, and water availability is increasingly limited: – Irrigation can reduce projected heat and drought stress (e.g., for wheat and maize) (Siebert et al., 2017; Ruiz-Ramos et al., 2018; Feyen et al., 2020). – Irrigation of wheat reverses yield losses across Europe at 2°C GWL to become gains, while yield losses in maize in SEU are reduced from as much as 80 to 11% (Feyen et al., 2020). – Changes to cultivars and sowing dates can reduce yield losses, but are insufficient to fully ameliorate losses projected at 3°C warming and above, with an increase of risk from north to south and for crops, such as maize, growing later in the season (Ruiz-Ramos et al., 2018; Feyen et al., 2020). – Use of longer-season varieties can compensate for heat stress on maize in WCE and lead to yield increases for NEU (Siebert et al., 2017; Ceglar et al., 2019). – Moving the growth cycle towards a cooler part of year reduces the period for photosynthesis and grain filling (Ruiz-Ramos et al., 2018; Holzkämper, 2020). – Physiological constraints, such as lack of sufficient light in winter and spring, might hinder exploitation of changes in phenology and hence the potential for longer growing seasons. – Crop breeding for drought and heat tolerance can improve sustainability of agricultural production under future climate (Costa et al., 2019b), particularly in SEU at 3°C GWL (Senapati et al., 2019). – Multifunctional land use can reduce the dependency on one crop and source of income (Holman et al., 2017). – Agricultural water management adaptation, such as irrigation, reallocating water to other crops, improving use efficiency and soil water conservation practices, reduces risks (Iglesias and Garrote, 2015). – In-season forecasts of climate impacts on yield were used during the 2018 drought for European wheat to inform policy actions (van der Velde et al., 2018). – There is greater need for pesticides to control and maintain production, due to range expansion and altered host pathogen association of pests, diseases and weeds affecting the health of European crops (Caffarra et al., 2012; Pushnya and Shirinyan, 2015; Latchininsky, 2017). – Simplifying procedures for obtaining subsidies and insurance premiums and interest rates can incentivise adoption of climate-friendly agricultural methods (Garrote et al., 2015; Iglesias and Garrote, 2015; Zakharov and Sharipova, 2017; Hamidov et al., 2018; Wiréhn, 2018). Water availability and competing uses is considered in KR3. Additional evidence from the F&E assessment is given in Table SM13.5.
Moderate to high risk	Does not reach this threshold	*medium*	Given high adaption, with the adoption of multiple options, including the availability of sufficient irrigation water and infrastructure, there is little evidence that the risk will reach this level. KR3 considers the availability of water and competing demand, but sufficient water availability required to supply crop irrigation is assumed for the risk level with high adaptation of KR2. See undetectable to moderate risk for the evidence above for evidence of adaption options (Table SM13.5), including irrigation. We concluded that under a high adaptation scenario, the risks do not reach this threshold.
High to very high risk	Does not reach this threshold	n.a.	As per moderate to high risk

Table SM13.29 | Transition and confidence levels for the risks of water scarcity to multiple interconnected sectors (Figures 13.28, 13.31)

Risk level	Range of temperature transitions (˚C GWL)	Confidence level for the transition	Explanation and references
Level of risk due to water scarcity in SEU with low adaptation			
Undetectable to moderate risk	0.7–1.1	*high*	There is already a moderate risk of water scarcity (according to the D&A in Figure 13.27). At 0.6˚C, 6 months of drought duration are estimated. In 1981–2010 (~0.7˚C), 48.1 million people were exposed to moderate water scarcity. Literature supporting this transition: Blauhut et al. (2015); Kebede et al. (2015); Blauhut et al. (2016); Gain et al. (2016); Gampe et al. (2016); Stahl et al. (2016); Bisselink et al. (2018); Byers et al. (2018); Naumann et al. (2018); Arnell et al. (2019); Harrison et al. (2019); Koutroulis et al. (2019); Bisselink et al. (2020); Cammalleri et al. (2020); Teotónio et al. (2020); Kebede et al. (2021); Naumann et al. (2021)
Moderate to high risk	1.3–1.7	*high*	– At 1.5˚C, 55.7 million (i.e., +7.4 million) people under moderate water stress – At 1.8˚C, Water Exploitation index increase of 230% and transition from moderate to high – At 2˚C, doubling of drought duration – At 2˚C, 54% of population water stressed – At 2˚C, drought duration 10 months Literature supporting this transition: Kebede et al. (2015); Gampe et al. (2016); Schleussner et al. (2016); Bisselink et al. (2018); Byers et al. (2018); Naumann et al. (2018); Tobin et al. (2018a); Arnell et al. (2019); Harrison et al. (2019); Bisselink et al. (2020); Cammalleri et al. (2020); Feyen et al. (2020); Teotónio et al. (2020); Kebede et al. (2021); Naumann et al. (2021)
High to very high risk	2.5–3.5	*medium*	– At 1.5˚C, 55.7 million people (i.e., +7.4 million) under moderate water stress – at 1.8˚C, Water Exploitation index increase of 230% and transition from moderate to high – At 2˚C, doubling of drought duration – At 2˚C, 54% of population water stressed – At 2˚C, drought duration 10 months Literature supporting this transition: Kebede et al. (2015); Gampe et al. (2016); Bisselink et al. (2018); Byers et al. (2018); Naumann et al. (2018); Tobin et al. (2018a); Arnell et al. (2019); Harrison et al. (2019); Koutroulis et al. (2019); Bisselink et al. (2020); Cammalleri et al. (2020); Teotónio et al. (2020); Kebede et al. (2021); Naumann et al. (2021)
Level of risk due to water scarcity in SEU with high adaptation			
Undetectable to moderate risk	0.9–1.3	*medium*	Improvements in water efficiency and in behaviour are very effective (>25% of damage avoided) in some SSP scenario improvements compared with baseline (Papadimitriou et al., 2019). There is some adaptation deficit now that can be addressed (see F&E water assessment in Table SM13.1). Literature supporting this transition: Papadaskalopoulou et al. (2015b); van Vuuren et al. (2015); Greve et al. (2018); Iglesias et al. (2018); Garnier and Holman (2019); Morote et al. (2019); Papadimitriou et al. (2019); and papers used in the F&E assessment (Table SM.13.1)
Moderate to high risk	1.8–2.2	*medium*	Investment in large water infrastructure and advanced technologies (including storage), water transfer, water recycling and reuse, and desalination (Papadaskalopoulou et al., 2015a; Greve et al., 2018) is needed. This will buy a bit of time in terms of coping with an increase of 0.5˚C GWL. Literature supporting this transition: Papadaskalopoulou et al. (2015b); van Vuuren et al. (2015); Greve et al. (2018); Iglesias et al. (2018); Garnier and Holman (2019); Morote et al. (2019); Papadimitriou et al. (2019); and papers used in the F&E assessment (Table SM.13.1)
High to very high risk	2.8–3.8	*low*	Transformational adaptation is needed, but ultimately planned relocation of industry and development of alternative livelihoods may be needed. Also, there are trade-offs with other adaptation options in need of water (Papadaskalopoulou et al., 2015a; Greve et al., 2018). Adaptation will buy a bit of time in terms of coping with an increase of 0.2˚C GWL. Literature supporting this transition: Papadaskalopoulou et al. (2015b); van Vuuren et al. (2015); Greve et al. (2018); Iglesias et al. (2018); Garnier and Holman (2019); Morote et al. (2019); Papadimitriou et al. (2019); and papers used in the F&E assessment (Table SM.13.1)

Risk level	Range of temperature transitions (˚C GWL)	Confidence level for the transition	Explanation and references
Level of risk due to water scarcity in WCE with low adaptation			
Undetectable to moderate risk	0.6–1.8	*medium*	– At 0.6˚C, 5.5–6.8 months of drought – At 1.5˚C, 6.8–8.3 months of drought – In 1981–2010 (~0.7˚C), 4.3 million people exposed to moderate water scarcity – At 1.5°C, 4.7 million people (i.e., +0.7 million) under moderate water stress – Number of people exposed is 1 order of magnitude smaller than in SEU (tens of millions) – Increase in exposure to moderate, but not severe, water scarcity (whereas severe water scarcity in SEU) – Population decline in continental Europe but population increase in France; overall reduced number of people exposed at 1.8˚C; Water Exploitation index increase of 60–200% – Low risk today (according to D&A) Literature supporting this transition: Blauhut et al. (2015); Kebede et al. (2015); Blauhut et al. (2016); Gain et al. (2016); Schleussner et al. (2016); Stahl et al. (2016); Bisselink et al. (2018); Byers et al. (2018); Naumann et al. (2018); Tobin et al. (2018a); Arnell et al. (2019); Harrison et al. (2019); Koutroulis et al. (2019); Bisselink et al. (2020); Cammalleri et al. (2020); Teotónio et al. (2020); Kebede et al. (2021); Naumann et al. (2021)
Moderate to high risk	2–3	*medium*	– At 2˚C, 16% of population exposed to at least moderate water stress – At 2˚C, 7–10 months of drought – At 3˚C, 8.8–14 months of drought – At 2˚C and 2.5˚C, a significant number of people exposed to drought in continental Europe and EEU – At 3˚C, significant drought losses also in WCE (50% of European GDP losses), particularly in Atlantic region Literature supporting this transition: Kebede et al. (2015); Schleussner et al. (2016); Bisselink et al. (2018); Byers et al. (2018); Naumann et al. (2018); Tobin et al. (2018a); Arnell et al. (2019); Harrison et al. (2019); Koutroulis et al. (2019); Bisselink et al. (2020); Cammalleri et al. (2020); Teotónio et al. (2020); Kebede et al. (2021); Naumann et al. (2021)
High to very high risk	4–4.5	*low*	– More strongly at 4˚C GWL, a significant number of people exposed to drought in continental Europe and EEU – At 4.5˚C GWL, Water Exploitation index increase of 200–310% Literature supporting this transition: Kebede et al. (2015); Bisselink et al. (2018); Byers et al. (2018); Naumann et al. (2018); Tobin et al. (2018a); Arnell et al. (2019); Harrison et al. (2019); Koutroulis et al. (2019); Bisselink et al. (2020); Cammalleri et al. (2020); Teotónio et al. (2020); Kebede et al. (2021); Naumann et al. (2021)
Level of risk due to water scarcity in WCE with high adaptation			
Undetectable to moderate risk	1.5–2.5	*low*	– There is high potential of water-efficiency improvements and water savings (>25% of damage avoided) in 50% of scenario improvements compared with baseline. – There is some adaptation deficit now that can be addressed (assuming an increase of 0.5˚C GWL). Literature supporting this transition: Collet et al. (2015); van Vuuren et al. (2015); Koopman et al. (2017); Greve et al. (2018); Manouseli et al. (2018); Garnier and Holman (2019); Papadimitriou et al. (2019); and papers used in the F&E assessment (Table SM.13.1)
Moderate to high risk	3–4	*low*	– There is considerable potential for investment in large water infrastructure and advanced technologies (including storage), water transfer, water recycling and reuse, and desalination. – As there is less of such infrastructure in place compared with SEU, there is high potential and effectiveness – (assuming an increase of 1˚C GWL). Literature supporting this transition: Collet et al. (2015); van Vuuren et al. (2015); Koopman et al. (2017); Greve et al. (2018); Manouseli et al. (2018); Garnier and Holman (2019); Papadimitriou et al. (2019); and papers used in the F&E assessment (Table SM.13.1)
High to very high risk	Not reached	n.a.	

Table SM13.30 | Transition and confidence levels for the risks of people, economies and infrastructures due to coastal flooding (Figures 13.28, 13.32)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
Level of risk due to coastal flooding with low to medium adaptation (keeping coastal protection as it is now)			
Undetectable to moderate risk	0.8–1.5	*medium*	Based on the D&A assessment in Figure 13.27, coastal impacts of climate change are starting to be detected in Europe (see Box 13.1), consistent with SROCC (IPCC, 2019).
Moderate to high risk	1.5–2	*medium*	Expected annual damage is projected to rise by a factor of at least 20 for 1.5–2.1°C GWL in EU-27 plus the UK (Vousdoukas et al., 2018); T values bounded by upper scenarios; supported by references in Sections 13.2 and 13.6; consistent with AR5 (Kovats et al., 2014) and SROCC (IPCC, 2019).
High to very high risk	2–3	*medium*	Expected annual damage is projected to rise by two orders of magnitude in EU-27 plus the UK above 2–3°C GWL (Vousdoukas et al., 2018; Vousdoukas et al., 2020); supported by references in Sections 13.2 and 13.6; consistent with AR5 (Kovats et al., 2014) and SROCC (IPCC, 2019).
Level of risk due to coastal flooding with high adaptation			
Undetectable to moderate risk	0.8–1.5	*medium*	Based on the D&A assessment in Figure 13.27 and the F&E assessment in Figure 13.11 and Table SM13.1; coastal impacts of climate change are starting to be detected in Europe (see Box 13.1); consistent with SROCC.
Moderate to high risk	1.5–3	*medium*	Expected annual damage is projected to rise by a factor of 10 above 2°C and by a factor of 20 above 3°C in EU-27 plus the UK (Vousdoukas et al., 2018; Vousdoukas et al., 2020). Transboundary risks can be limited with high adaptation (Mandel et al., 2021). See also Sections 13.2 and 13.6, Table SM 13.1 and references therein. Data are consistent with AR5 (Kovats et al., 2014) and SROCC (IPCC, 2019).
High to very high risk	n.a.	n.a.	Does not reach this threshold
Level of risk from delayed impacts of SLR to cultural heritage and long-living infrastructure			
Undetectable to moderate	0.5–1.2	*low*	Except in Fennoscandia, European sea levels are projected to rise at rates and magnitudes close to the global average (Fox-Kemper et al., 2021), including Mediterranean Sea levels (SMCCP4.2, SMCCP4.4). Pre-industrial temperatures led to steady sea levels (Fox-Kemper et al., 2021), and historical greenhouse gas emissions are projected 0.7 to 1.1 m of SLR by 2300 (Fox-Kemper et al., 2021), based on Nauels (2019). Compared with other regions, Europe and particularly SEU is characterised by a very high number of UNESCO World Heritage sites exposed to SLR (Marzeion and Levermann, 2014; Reimann et al., 2018). This includes Venice, where high-tide flooding has increased consistently with relative sea level changes (see Box 13.1).
Moderate to high	1.2–1.5	*low*	Sea levels are projected to rise between 0.3 and 3.1 m by 2300 under SSP1–2.6 (*low confidence*) (Fox-Kemper et al., 2021). Sea levels are projected to rise by 2–3 m after 2000 years, and by 6–7 m after 10,000 years, for 1.5°C GWL, but these long-term projections incorporate processes in which there is *low confidence* (Fox-Kemper et al., 2021). The number of UNESCO World Heritage sites exposed to flooding (erosion) increases with SLR, and so do flood frequencies, intensities and erosion rates (Reimann et al., 2018).
High to very high	1.5–2	*medium*	Sea levels are projected to rise between 0.3 and 3.1 m by 2300 under SSP1–2.6 (*low confidence*) (Fox-Kemper et al., 2021). Sea levels are projected to rise by 2–6 m after 2000 years, and by 8–13 m after 10,000 years, for 2°C GWL, but these long-term projections incorporate processes in which there is *low confidence* (Fox-Kemper et al., 2021). In at least 12 countries in Europe, stabilisation of global warming at about 2°C would lead to drowning areas, after millennia, where at least 10% of the population currently live (Clark et al., 2016).

Table SM13.31 | Transition and confidence levels for the risks of people, economies and infrastructures due to inland flooding (Figures 13.28, 13.32)

Risk level	Range of temperature transitions (°C GWL)	Confidence level for the transition	Explanation and references
Level of risk due to inland flooding with low adaptation			
Undetectable to moderate risk	0.5–1.3	*high*	The same references were used as for Figure 13.27 (Table SM13.22); additional evidence from the trends in the hazards (pluvial floods) (Ranasinghe et al., 2021; Seneviratne et al., 2021) and based on independent expert assessment of the literature of two lead authors and additional support of two contributing authors. The upper value for this transition is 1.3°C GWL because it is within the likely range for observed global warming from pre-industrial levels (see Cross-Chapter Box 2.3 in Gulev et al., 2021) and to distinguish from the impacts at 1.5°C GWL, which have been assessed to be well within the moderate risk level. Namely, the lead authors considered the potential for severe consequences to happen sooner rather than later (i.e., before reaching 1.5°C) given the persistence of certain conditions in the hazards (Ranasinghe et al., 2021; Seneviratne et al., 2021) and exposure (high population density along river banks and urban infrastructures difficult to change). For example, 22% of flood damage losses were in Europe (second after Asia) between 1976 and 2005 (Dottori et al., 2018); 8–26 billion EUR in economic losses; affected potential population per year: 156–679 10^3 (Alfieri et al., 2018); and at 1°C GWL, the population exposed to 100-year return discharge increases by 3–30% in some grid cells in WCE and NEU (Lange et al., 2020). However, there is also evidence that vulnerability is decreasing. For example, there has been an increase in annually inundated area and the number of people affected since 1870 but no significant trend in normalised financial losses from 1970 to 2006); substantial decline in fatalities since 1950; contrast between NEU and SEU; and increased hazard but decreased vulnerability of population and assets (Paprotny et al., 2018).
Moderate to high risk	1.5–2.5	*medium*	The level of risk is based on quantitative flood hazard projections (Ranasinghe et al., 2021), flood risk projections (Ciscar et al., 2014; Jongman et al., 2014; Alfieri et al., 2017; Ciscar et al., 2018; Arnell et al., 2019; Harrison et al., 2019; Dottori et al., 2020; Hosseinzadehtalaei et al., 2020; Lange et al., 2020; Merz et al., 2021), considering the potential for cascading risks as part of the criteria for key risk severity (Chapter 16) and considering that limited adaptation has put human lives at risk from flooding.
High to very high risk	2.5–3	*medium*	The level of risk is based on projections suggesting that flood hazard and risks continue to increase above 3°C GWL (Sections 13.2, 13.6; Alfieri et al., 2017; Hosseinzadehtalaei et al., 2020) and considering the limited ability of current systems to protect and accommodate flooding. At 3°C GWL, evidence suggests that the magnitudes of severe consequences increase considerably, and such consequences are also more widespread for both economic damage and people affected. Therefore, very high risks are plausible beyond 3°C GWL (e.g., at 3°C GWL, around 600–700 billion EUR in damage in WCE compared with approximately 100 billion EUR in the baseline). We also observe approximate quadrupling in part of Russia (Merz et al., 2021). Furthermore, under SSP5 welfare losses (compared with SSP5 baseline without climate change), WCE is –0.17% and Russia is –0.52%; however, indirect losses are increasing more strongly than direct losses between 1.5°C and 3°C GWL because of the persistence of the damage to the economy (Dottori et al., 2018). For Europe in total, there is a slight increase in the population exposed; the difference between 1.5°C and 3°C GWL is not significant (Dottori et al., 2018). At 4°C GWL, there is an 87% increase in pluvial flood risks (Hosseinzadehtalaei et al., 2020). There is *medium confidence*, however, given that the evidence finds population exposed to riverine flooding to increase strongly (up to 300%) in NEU, as well as in central and western parts of WCE, but to decrease in eastern parts of WCE. There is also a slight increase in SEU.
Level of risk due to inland flooding with high adaptation			
Undetectable to moderate risk	0.5–1.5	*medium*	The same references were used as for Figure 13.6 (Table SM13.1); additional evidence from the trends in the hazards (pluvial floods) (Ranasinghe et al., 2021; Seneviratne et al., 2021). The higher transition reflects higher adaptation potential (e.g., 1.5°C GWL under RCP2.6 and SSP1/SSP4), and the population exposed to coastal and riverine flooding decreases by >25% in alpine, northern, continental and southern Europe and increases or stays constant on the Atlantic coast (Papadimitriou et al., 2019). Up to around 1.6°C GWL, increasing flood protection levels in all basins to a minimum of 1 per 100 years would decrease the total expected annual flood losses by 30% (A1B-2050) (Jongman et al., 2014). If insurance penetration increases from 30 to 50%, uninsured losses would drop by 60% (Jongman et al., 2014).
Moderate to high risk	2.5–3	*medium*	The level of risk is based on quantitative flood risk projections under SSP5 (Alfieri et al., 2017; Arnell et al., 2019; Harrison et al., 2019), considering that flood damage in Europe could be offset by adaptation (Jongman et al., 2014; Alfieri et al., 2016a; Dottori et al., 2020), that city drainage systems are difficult to upgrade and the empirical evidence that city adaptation currently remains slow (Ürge-Vorsatz et al., 2018). Under 3°C GWL, the same number of people would be exposed but with a 12% reduction in damage (i.e., river flood) using building-scale measures (Dottori et al., 2020). If we approximate high adaptation under SSP1 conditions, at 4°C GWL, there would be 14–23% less increase in pluvial flood risks under RCP4.5/SSP1 compared with RCP8.5/SSP5 (where the increases is 87%) (Hosseinzadehtalaei et al., 2020); however, the residual risk still would be considerable. Furthermore, there is persistence of hazard and exposure conditions as well as limitations in drainage systems (Dale et al., 2018; Dale, 2021). Additional evidence is given in the F&E assessment (Table SM13.1).
High to very high risk	n.a.	n.a.	Does not reach this threshold

SM13.11 Supplementary Material Supporting the Development of Adaptation Pathways

This section describes the approach used to derive the illustrative adaptation pathways underpinning Figures 13.29–13.32. Adaptation pathways are established in scientific literature on climate adaptation planning to support decision making under deep uncertainty and break adaptation into manageable steps over time. Adaptation pathways map possible sequencing of adaptation options (or portfolio of options or strategies) as a function of global warming (global surface air temperature) and/or time. The basis for deriving adaptation pathways in Chapter 13 follows the methods described in Haasnoot (2013) and Haasnoot (2019). The adaptation pathways are built on the results of the burning embers developed for the key risks (Section 13.10.2), as well as selection of adaptation options and the assessment of their feasibility and effectiveness in Sections 13.2.2, 13.5.2, 13.6.2 and 13.7.2.

Methodology for Deriving the Illustrative Pathways in Chapter 13

Step 1: Decide on the scope and narratives of the adaptation pathways.

In step 1, the author team developed the pathway narrative based on the key risk aggregation (Section 13.10.2) and the aggregation of the options in the feasibility and effectiveness (F&E) assessments described in Tables SM13.1, SM13.5, SM13.15 and SM13.19. Through discussions, the teams decided on the type of illustrative pathways for the different key risks, for example, for each of the European regions (SEU, NEU, EEU and WCE) or hazard type (e.g., coastal and riverine flood). Based on the burning embers and the F&E assessments, suitable combinations of measures and their sequencing were agreed and translated into narratives supporting the pathways. Only measures with at least *medium confidence* were considered. Each statement has full traceability to the F&E assessment tables in the Supplementary Material.

Step 2: Construct the pathways.

The available information on effectiveness to reduce risk per GWL or time was used when available. In the absence of such information, evidence was used from adaptation options already implemented that have demonstrated medium to high effectiveness in reducing risk. Based on the inventory of adaptation options, the relative effectiveness (e.g., A is better than B in reducing risk) was determined.

Path dependencies were identified during discussions with the team (e.g., if option A is implemented then option B is not possible, difficult to implement or not logical). Storylines and narratives were used to describe the implementation of adaptation options over time (e.g., first option A, then option B, and if risk increases further, then C or D is a long-term option). Changes in GWLs affecting these options, the path dependency of options and feasibility of implementation were considered. Pathways typically started with low-regret options that allowed adding more adaptation options and reducing risk under different levels of warming.

Statements developed in step 1 were aggregated to facilitate graphic visualisation, and to be presented in the text. Confidence levels were assigned to the statements. Several intermediate versions of the pathways were drafted and then discussed with the author team until consensus was reached. When the effectiveness of measures was dependent on the region or the hazard, different pathways maps were designed, for example for Key Risk 1 (heat and human health). All pathways are visually presented using the following logic:

- Measures belonging to a similar strategy (e.g., protect or resist) or similar type of measures (e.g., engineering measures) are presented close to each other in the figure.
- The current situation is indicated in the centre.
- Adaptation measures that reduce risk only at low GWLs (thus low effectiveness) are shown close to the present situation, and options with higher effectiveness at higher GWLs are either on the top or bottom of the figure, as such pathways typically start in the centre of the pathway map (close to the present) and move towards the outer corners.
- When two or more measures are needed to reduce the risk, their respective lines are joined.

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