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Review article

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Compound heat and moisture extreme impacts on global crop yields under climate change

Corey Lesk[1,2,3], **Weston Anderson**[4,5], **Angela Rigden**[6,7], **Onoriode Coast**[8], **Jonas Jägermeyr**[9,10,11], **Sonali McDermid**[9,12], **Kyle F. Davis**[13,14] & **Megan Konar**[15]

Abstract

Extreme heat, drought and moisture excess are increasingly co-occurring within a single growing season, impacting crop yields in global breadbasket regions. In this Review, we synthesize understanding of compound heat and moisture extremes, their impacts on global crop yields and implications for adaptation. Heat and moisture extremes and their impacts become compounded through crop-physiological interactions, heat–moisture couplings in the climate system and crop–atmosphere interactions. Since around 2000, these compound extremes, and hot droughts in particular, have been linked to especially poor harvests (up to 30% yield losses) in regions such as India, Ethiopia, the USA, Europe and Russia. However, in some cases, combinations of crop stresses might generate compensating effects. Compound extremes are projected to increase in frequency and amplitude in the future, but, owing to the biophysical interdependence among temperature, water and crop physiology, the net yield effects of such future compound extremes remain uncertain. Accordingly, compound extremes will necessitate comprehensive agricultural adaptation strategies geared towards multi-stress resilience, as adaptations that work for single climate stresses could be maladaptive under combined stresses. An integrated understanding of heat and water in soil–plant–atmosphere dynamics is urgently needed to understand risks and suitably adapt cropping systems to compounding climate impacts.

Sections

A full list of affiliations appears at the end of the paper. e-mail: corey.s.lesk@dartmouth.edu

Introduction

Productive crops underpin the global food system, stable commodity prices and rural livelihoods. Climate is a major driver of staple crop production variability, accounting for up to 50% of year-to-year variation in global crop yields[1,2], particularly via extreme events[3]. As climate-related hazards mount, extreme heat, drought (precipitation or soil moisture deficits) and excess moisture are increasingly co-occurring in space and time[4–7]. Such combined stressors, or 'compound extremes' (multiple, potentially interacting hazards that generate multiple, potentially interacting impacts, contributing to societal or environmental risk[4]) can have unique and particularly severe crop impacts.

The myriad complex interactions involved in compound temperature and moisture extremes pose a challenge to understanding how climate variability affects crop yield. For example, early efforts to statistically model empirical crop–climate relationships revealed a particular sensitivity of staple crop yields to extreme heat[8,9]. Although extreme temperatures can directly damage crop tissue and reduce yield capacity, they can also induce moisture stress by raising the evaporative demand of the atmosphere (vapour pressure deficit (VPD))[10,11]. Land-surface drying also often amplifies high air temperatures, physically linking the two extremes[12,13]. Furthermore, responses of crop physiology to combined drought and heat stresses are distinct from those of the individual stresses[14,15] and often more severe[16]. Such connections between water and heat in the physics of climate extremes and their impacts on crop biology raise the potential for compound, interactive effects of changing precipitation, temperature, soil moisture and VPD.

Future changes in crop productivity will also depend on the evolution of many climate variables and their interactions under anthropogenic greenhouse gas increase. However, projections of some of these variables are highly uncertain. Critically, the response of soil moisture to climate warming is complicated by uncertainty over future changes in precipitation and its partitioning to soil moisture, runoff and evapotranspiration[17–21]. Future warming is, by contrast, projected with high confidence. Therefore, the degree to which warming will benefit or limit crop yields will ultimately depend on hydrological variables and their co-variability with temperature. The emerging mechanistic understanding of compound climate impacts on crops thus raises new scientific questions and presents challenges for adapting crops and farming systems to climate change.

In this Review, we synthesize and interpret advances in the understanding of past and likely future impacts of compound extremes. We focus on compound extremes occurring within a single growing season at a given location on global crop production, with emphasis on yield. We first propose and interpret three modes by which climate impacts on crops can become compounded. We then assess historical and projected future trends in compound extremes and their impact on crop yields. With this conceptual and prognostic basis, we identify new strategies to limit risks and maximize opportunities of compound extremes and climate change for crops and farming. Although the focus is on biophysical dimensions, key implications for social aspects of food systems and security are briefly discussed.

Compound extreme and crop impact dynamics

Climate impacts on crops can be compounded via three primary modes (Fig. 1). First, interactions among crop-physiological responses to different aspects of climate can worsen or ameliorate the ultimate yield effect (Fig. 1, green boxes). Second, heat–moisture interactions in the climate system can generate or amplify compound extremes, such as

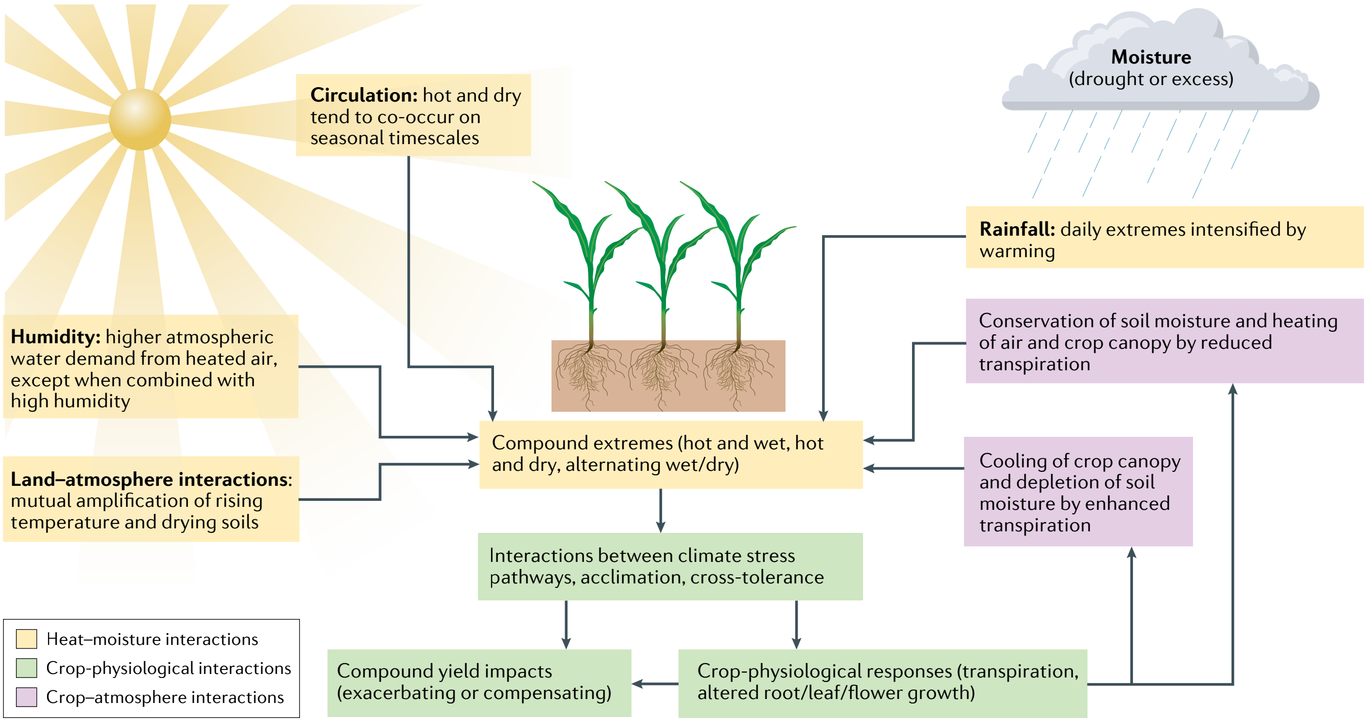


Fig. 1 | Compounding climate influence on crop yields. Summary of the processes generating compound extremes and their resulting crop impacts, including heat–moisture interactions, crop-physiological interactions and crop–atmosphere interactions. Compound extremes and their unique crop impacts are largely governed by these three modes.

combined and interacting heat and drought hazards (Fig. 1, yellow boxes). Third, the dynamic interaction of climate hazards and crop-physiological responses, or crop–atmosphere interactions, can modulate the hazard through positive or negative feedbacks[22] (Fig. 1, purple boxes). Other biotic and abiotic interactions also cause compound climate–crop impacts, including toxicity from high atmospheric concentration and plant absorption of ozone during extreme heat[23]; joint enhancement of crop vulnerability and disease proliferation during warm and wet conditions[24]; wind, salinity and excess moisture stresses from compound flood and storm events[25]; and suppression of nutrient cycling by the soil microbiome during climate extremes[26]. However, focus is placed on the three modes, given their particular salience for compound heat and moisture extremes.

Crop-physiological interactions

Individually, heat, drought and excess moisture influence crop physiology and yield process through various mechanisms. Heat or drought can reduce crop yield by limiting carbon assimilation through photosynthesis, increasing carbon loss via respiration and restricting transpiration. Drought stress progressively reduces photosynthesis, initially through partial closure of stomata (decreasing CO_2 capture), and as the deficit continues, via reduced photosynthetic capacity[27] and damage to hydraulic tissues. Under thermal stress, chloroplast proteins and membranes are compromised and stomates often close to prevent water loss[28], similarly reducing photosynthesis. Short-term high temperatures also boost respiratory release of CO_2 by denaturing proteins and membranes, requiring energy to repair[28,29], and thus widening the gap between carbon gain and loss. Heat further impedes seedling development through reduced rates of leaf expansion; partial or complete failures of flower and seed development[30,31]; and reduced capture of light, water and nutrients through accelerated crop development.

Excessively wet conditions are also disruptive to crop yield processes through various means. Climate events leading to excess soil moisture can physically damage aboveground crop biomass through heavy precipitation and wind[32]. The ensuing excessive soil moisture impedes gas exchange in the rhizosphere, depriving roots of oxygen needed for aerobic respiration and energy production. Such rhizosphere anoxia leads to the generation of reactive oxygen species that cause oxidative damage to organelles and cells. Excess moisture stress thus shifts crop energy use away from yield-generating processes (such as nutrient uptake and growth) towards survival, which could ultimately lead to crop death[33,34]. Root tip tissues damaged by waterlogging also struggle to absorb nutrients and water from the soil[35], whereas waterlogging itself can limit nutrient availability by leaching soluble nitrates and promoting anaerobic denitrification by microorganisms, with lasting consequences for soil fertility[26]. Most crops are not well adapted to such excessively wet conditions, one exception being rice, which develops adventitious roots with aerenchyma to facilitate gas diffusivity from aerial regions to the flooded roots[36,37].

These basic crop-physiological responses to univariate extremes have drawn much attention. However, when multiple extremes occur together or during the same growing season, interactions between response mechanisms to univariate climate extremes can lead to compound impacts (Fig. 1, green boxes), the mechanisms of which are often distinct from individual stresses. Such multi-stress responses are governed by interactions between different aspects of crop physiology — including crop metabolic[38], signalling[39] and morphological responses[40] — that are physiologically linked in ways that can worsen[41] or alleviate[42] the ultimate climate impact on yield[43]. These responses affect key yield processes such as the balance of carbon capture and energy efficiencies of photosynthetic and respiratory processes[44]; water and nutrient uptake[45]; and transport and utilization of stored assimilates[44].

Stomatal responses provide a key example of these multi-stress responses. Plants typically close stomata to maintain water status during drought. But at very extreme high temperatures, plants might re-open stomata to thermoregulate via transpiration and limit damage. During combined heat and drought, the drought response might dominate: stomates close and leaf temperatures might increase to damaging levels[46]. Such stomatal responses to combined stresses are regulated by unique signalling pathways, generating physiological outcomes that vary based on growth stage, crop type and different combinations of stresses[47]. At the same time, other signalling pathways induced by heat or drought can aid acclimation of photosynthesis and respiration to repeat stresses[42].

Thus, crop-physiological responses to combined extremes are often complex and cannot be adequately inferred from the responses to the individual components[14,41,47]. In addition, the order of occurrence of these extremes (co-occurring or sequential)[4] elicits varying degrees of complex responses — defined by different and sometimes contrasting signalling pathways[39]. The ultimate yield impacts of climate extremes therefore reflect intertwined physiological responses to multiple aspects of climate.

Heat–moisture interactions

Physical interactions between heat and moisture in the climate system induce dependence between climate variables, influencing the likelihood of compound extremes[48] (Fig. 1, yellow boxes). These processes include feedbacks between atmospheric drivers and land-surface responses (land–atmosphere interactions) and atmospheric connections among heat, atmospheric humidity and rainfall.

Several aspects of the atmospheric dynamics behind heat extremes cause them to co-occur with dry conditions. Heatwaves are often driven by atmospheric blocking, resulting in high-pressure atmospheric circulation patterns favouring clear skies, warm and descending winds and high solar radiation[49]. This circulation pattern is generally unfavourable to precipitation[50]. Partly as a result, growing season temperature and precipitation are anticorrelated across most of the global land area in both climate models (Fig. 2a) and observations (Fig. 2b), enhancing the likelihood of simultaneous hot and dry anomalies (Fig. 2c). Strong heating of the land surface subsequently leads to progressive warming and drying of the atmospheric boundary layer[51], further increasing incoming radiation by reducing cloud cover[52] and decreasing local precipitation recycling[53]. These circulation-linked interactions amplify[54], mitigate[55] or shape the timing and location[56] of concurrent hot and dry extremes by altering moisture convergence or monsoon onset.

Changes in the partitioning of energy at the land surface during the onset of a heatwave or drought further raise the likelihood of a concurrent heatwave and drought. In general, only a portion of the incoming radiation leads to warmer surface temperatures (sensible heating), whereas most fuels evapotranspiration (latent heating). If the land surface becomes water-limited, air temperatures rise more quickly as energy is partitioned to sensible heating. Hotter temperatures then boost the drying of soils, creating a positive feedback[52,53]. This feedback occurs most strongly in zones that are semi-humid to semi-arid (that is, transitional zones), including important breadbaskets in Eurasia and the North American Great Plains[48]. However, the reverse of this feedback

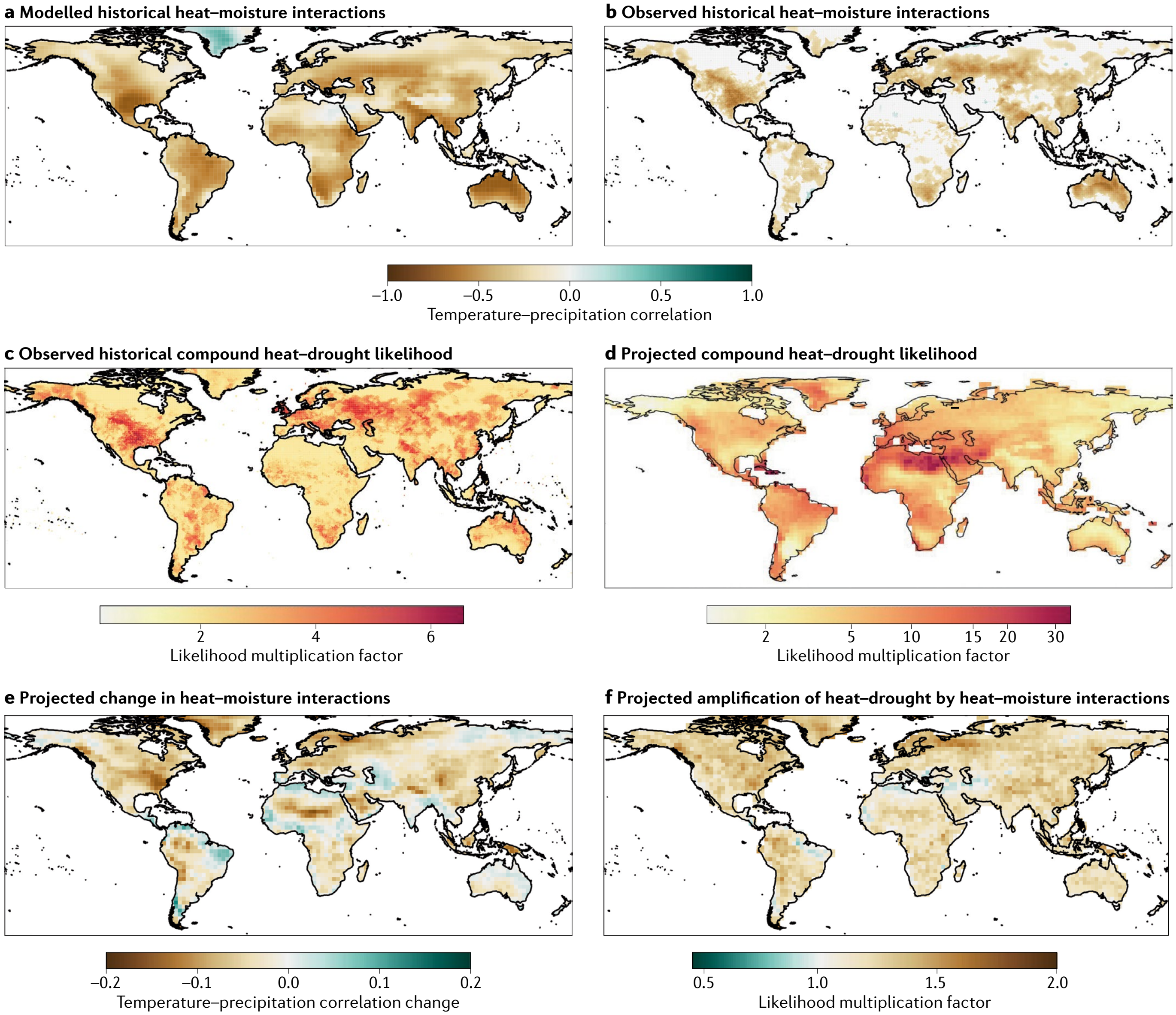


Fig. 2 | Historical and projected future heat–moisture interactions and compound heat and drought. a, Historical (1870–1969) interannual correlation between warm-season mean temperature and total precipitation on average across 40 models from the Coupled Model Intercomparison Project Phase (CMIP) 5 (reviewed elsewhere[215]). **b**, Historical (around 1900–2010) interannual correlation between warm-season mean temperature and total precipitation averaged across the Hadley CRU, Princeton and Delaware observational datasets[216–218]. **c**, Observed historical (1870–1969) likelihood of compound heat and drought (concurrent exceedance of 90th percentile warm-season high temperatures and low precipitation) during the warm season arising from the dependence between temperature and precipitation. **d**, Projected change in the likelihood of warm-season compound heat and drought in climate models from climate change. **e**, Projected change in interannual correlations between warm-season temperature and precipitation. **f**, Projected change in the likelihood of compound heat and drought in climate models linked to the change in interannual correlation between temperature and precipitation. Data in **d**–**f** reflect the average of 40 CMIP5 models for the late twenty-first century under the RCP8.5 high-emissions scenario versus a historical baseline of 1870–1969. In most cropping regions, heat–moisture interactions in the climate system enhance compound heat and drought extremes, both historically and under projected warming. Figure adapted, with permission, from ref.[48], AAAS.

occurs in more humid mid-latitude and tropical breadbaskets, where increased evapotranspiration can cool summertime temperatures[53,57]. Land–atmosphere interactions thus strongly influence the direction and strength of the coupling between the heating of air and drying of the land surface, and therefore there is a tendency for hot and dry conditions to co-occur.

The biological response of natural vegetation to climate further alters the evolution of compound climate extremes regionally[58,59], beyond the purely physical aspects of land–atmosphere interactions. Over regional scales, land–atmosphere interactions are closely related to variations in transpiration by natural vegetation, which dominates the global flux of moisture from land to atmosphere[58,60]. Reduced transpiration from stomatal closure by forests or grasslands experiencing high temperatures and VPD conserves soil moisture, but boosts land temperatures[12,61], affecting the climate of adjacent croplands.

The moist thermodynamics of air further increase the likelihood of concurrent hot and dry conditions as warmer air tends to be dryer in terms of VPD. This tendency exists because the water vapour holding capacity of air at a given humidity level rises non-linearly by approximately 7% per degree Celsius (as described by the Clausius–Clapeyron relation). For example, at a fixed relative humidity of 20%, the VPD of air nearly doubles between 25 and 35 °C, exerting nearly twice the drying power on crops[10]. Warmer air thus carries more water away from crops and, as a result, extreme heat can induce direct heat stress and indirect moisture stress through high VPD. However, this heat–VPD link is weakened during compound humid-heat extremes[62], in which high temperatures accompanied by high humidity generate heatwaves with low VPD[63]. Atmospheric circulation patterns conducive to such events are common during growing seasons in important crop regions such as the USA and South Asia[63,64].

Warmer conditions are also linked to higher-intensity short-duration rainfall events. The obverse of the Clausius–Clapeyron relation is that warmer air carries and delivers more water vapour to clouds at a rate of 7% per degree Celsius, fuelling heavier rainfall intensities, especially at hourly to daily scales[21]. Furthermore, warmer and wetter air favours rising winds (convection), fuelling thunderstorms and boosting the intensity of extreme rainfall events[21] well beyond 7% and up to 40% per degree Celsius. As such, compound extreme heat–precipitation events are thus relatively common. In China, for example, 23% of precipitation extremes were preceded by a heat event during 1960–2016 (ref.[65]).

A general effect of heat–moisture interactions is to induce dependence between various crop-relevant aspects of climate[48] (Figs. 1 and 2a,b). This dependence contributes to the genesis of compound temperature and moisture extremes (Fig. 2c), which often have distinct crop impacts. However, heat–moisture interactions also induce correlations between climate variables (Fig. 2a,b), which pose methodological challenges to disentangling the causality of their crop effects (Box 1).

Crop–atmosphere interactions

Crops, and their evolving management by farmers, meaningfully alter regional land-surface properties[59]. As such, crop-physiological responses to climate variation shape local climate extremes, often

Box 1

Assessing the crop impacts of compound extremes

The crop impacts of compound extremes involve interactions among multiple hazards and the resulting crop-physiological responses. Disentangling these closely connected causes and effects poses a considerable methodological challenge that has been partly addressed through advances in data, modelling and analysis.

Physiological impacts of univariate climate extremes on crop yield processes are well understood at the plant-to-field scale from laboratory and field experiments. However, detailed measurements of plant biology are unfeasible at the larger spatial scales relevant to regional and global food security. Statistical crop models are one tool by which the understanding of univariate climate extreme impacts on crop yields has been extended towards larger spatial scales. This modelling framework, which estimates yield responses based on seasonally aggregated exposure to specific temperatures, has been used extensively[8,117] (Fig. 3). However, it often applies multiple regression techniques that can be limited in attributing yield impacts to the various correlated climate anomalies that occur within a growing season[86]. By flexibly modelling multivariate dependence, copula[93] and machine learning[3] methods can help to surmount these limitations and improve the reliability of projections.

Process-based crop models, which simulate the growth environment and physiology of crops, provide a mechanistic counterpart to statistical models[121]. These models enable controlled simulation experiments that can help to shed light on the causality of compound climate impacts on crops[94]. However, certain processes relevant to compound climate influences on crops, such as stress interactions and crop–atmosphere feedbacks, are incompletely represented in such models[32,95], probably resulting in biased future yield projections.

Data and experimental advances since 2010 have helped to overcome challenges in both modelling frameworks. Applications of satellite observations of near-surface soil moisture, for instance, from the Soil Moisture Active–Passive project[83], have provided the most direct evidence of the importance of soil water supply relative to atmospheric demand for large-scale crop yields[84,85]. These results help to provide mechanistic clarity on the particularly severe yield effects of combined heat and drought[16], which can be incorporated into process-based crop models. Statistical crop model performance also improves by ~5–20% when both moisture and temperature are explicitly (and appropriately) included[84,85].

Diverse metrics of compound extremes are used across the climate and crop literature, which complicates building consensus behind emerging conclusions. For instance, soil moisture, precipitation and derived metrics such as the Standardized Precipitation Index are a few examples of ways that crop water supply can be represented[85,86]. Compound extremes can be identified as simultaneous exceedances of absolute (physical units) or relative (percentile or standard deviation anomaly) thresholds, or as tail values of a joint distribution, among other methods. Although diverse metrics help to encapsulate complex compound extremes and their impacts, greater coherence across research would aid building consensus in which signals are clear and diagnosing drivers of uncertainty where they are not. For example, soil moisture probably affords a more direct metric of crop-available water than precipitation, notwithstanding its complex interactions[85,86].

in ways that modulate compound extremes (Fig. 1, purple boxes). Crops have both cooling and warming effects on air and canopy temperature, and wetting and drying effects on soil moisture, all of which are mediated by variations in transpiration. These effects span spatial scales from canopy microclimate to wider cropping regions.

In some densely cropped regions, crops cool themselves and the land surface through transpiration, limiting detrimental heat extremes[66,67]. Yet in doing so they deplete soil moisture[68,69]. However, crops also reduce transpiration under water stress, conserving soil moisture but potentially amplifying local temperatures[70]. The magnitude of the warming effect of stomatal limitation during droughts can be substantial, reaching 7–10 °C[68,70] at the field scale. Crop responses to extreme heat thus tend to have countervailing effects on soil moisture and vice versa. As such, the interaction of climate stresses and crop responses modulates the concurrence of climate stresses. However, this tendency can be altered by irrigation, enabling crops to continue transpiring during extreme heat and drought[71].

As a result of these interactions, crops experience local microclimates that differ from the wider region or even from the overlying atmosphere[68,70]. The thermoregulating effect of transpiration most directly affects internal and surface temperatures of crop tissue[44]. As a result, leaves, flowers and even the wider vegetated canopy can be cooler or warmer than the surrounding air[68,72]. In China and India, these crop influences on surface climate extend through the troposphere[73] and influence large-scale circulation and rainfall patterns[74]. Many crop physiological responses to climate extremes, in turn, affect the climate experienced by the crop, both locally and regionally. These mutual influences between climate extremes and crop impacts additionally link the co-evolution of heat and moisture extremes, both locally and regionally.

Univariate versus compound extremes

Although compound climate extremes constitute a unique and escalating set of hazards to crop yields, the three modes of compounding are often at play during univariate extremes. Indeed, the dynamics of many univariate extremes and their crop impacts often involve interacting stresses and physiological responses, and so are inherently compound to some extent. Considering extremes typically considered univariate through the lens of compound extremes has led to conceptual and methodological advances.

The impact of extreme heat on crop yields, as captured by statistical crop–climate models (Box 1), illustrates the implications of these modes of compounding for a crop-relevant climate extreme that is often conceived as univariate. Strong regional crop yield declines from temperatures above ~30 °C were revealed by early statistical analyses[8,9]. Although such empirically derived temperature thresholds for damage vary depending on crop type, region and growth stage, they are often 5–10 °C lower than expected from plant-scale analyses[31,75,76]. This tendency, combined with experimental insights from process-based crop models[77,78], suggests that the relationships between temperature and yield at larger spatial scales are probably confounded by water availability. High temperatures tend to co-occur with both low soil moisture[13,53] and high VPD[12,79], such that field crops rarely experience the effects of heat in isolation (Fig. 3a).

The natural experiment of comparing the impacts of climate extremes on irrigated versus rainfed crops provides a further glimpse of the pervasive influence of modes of compounding. When soil moisture is managed via irrigation, the resolved empirical relationship between yield and extreme heat is typically weakened[80], with yield loss occurring at a higher temperature[77]. Such findings demonstrate that heat damages depend on water status. However, irrigation also cools local air temperatures[81], raising the question of

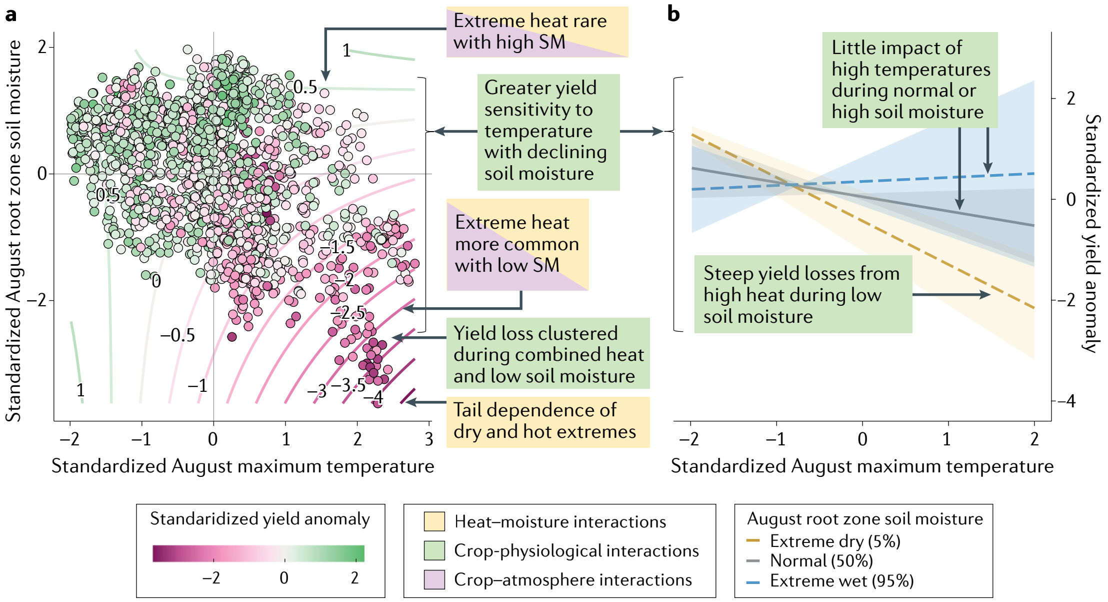


Fig. 3 | Soybean yield responses to soil moisture and temperature variation. **a**, Observed standardized soybean yield anomalies (points) and contour fits (lines) situated in the space of standardized August temperature and root zone soil moisture anomalies. Data are for counties in IL, USA, between 1982 and 2016. **b**, Sensitivity of soybean yield anomaly to temperature for three different root zone soil moisture percentiles (5th, 50th and 95th). Shaded annotations represent the three modes by which climate impacts on crops can be compounded. Three modes of compound climate impacts on crops are visible in the results of statistical analyses of real-world crop and climate data. SM, soil moisture. Figure adapted from ref.[88] under a Creative Commons licence CC BY 4.0.

whether it bolsters yields by improving water availability[82] or buffering extreme heat[66].

The emergence of more direct soil moisture observations has enabled disentangling and diagnosing correlated climate drivers of crop yields[83] (Box 1). Analyses using such observations provide the most direct evidence of the importance of soil water supply for crop yields relative to atmospheric demand[84–86]. They explain the resistance of irrigated crop yields to high temperatures that would strongly suppress the yield of rainfed crops[77,87]. They further provide mechanistic clarity on the particularly severe yield effects of combined heat and drought[16].

Although temperature alone is a powerful statistical predictor of crop yields, its ultimate influence depends on a host of additional climate factors. Crop yield responses to warmer temperatures depend on precipitation[16] and soil moisture[85] (Fig. 3). Yield declines are most marked[84,88] and probable[89] when heat coincides with dry conditions, whereas yields benefit from warmer temperatures during above-normal moisture, especially at sensitive growth stages[84,88] (Fig. 3b). However, extreme wet conditions are associated with yield losses[32] during both cool[85] and warm[90] anomalies. Model estimates vary widely on the overall relative importance of moisture versus temperature historically[78,84] and under further warming[85,91]. This tendency is perhaps indicative of underlying uncertainties in the causal pathway.

These confounding effects of coupled heat and water stress, which operate from the molecular through to the regional scales, demonstrate the limitations of univariate extremes for understanding the influence of climate on field crops. Compound extremes and climate changes are more reflective of the most crop-relevant field conditions[47], hazards and damage pathways. Although it is clear that crops are sensitive to joint variations and extremes of climate variables, discerning the true causal pathway of impacts still remains challenging. For instance, the reduction in heat impacts under wet conditions has been attributed to a positive effect of moisture, independent of heat stress[32,91,92]; reduced compounding of heat stress by water stress[93,94]; or reduced heat exposure due to the cooling effect of elevated soil moisture[71,82] (Fig. 3a). Correctly specifying this causality in process-based[92,95] and statistical crop models is essential to understand and reliably project yield responses to compound extremes under ongoing climate warming. Uncertain changes in precipitation, humidity and soil moisture[19,96], as well as crop physiology and temperature–moisture co-variability[48,57], further complicate the task of projecting future yields and anticipating effective adaptation strategies.

Historical trends

Compound heat and moisture extremes have become more intense and frequent in many cropping regions since the mid-twentieth century[97,98], in many cases leading to substantial yield losses (Fig. 4). These changes and their impacts are discussed subsequently.

Historical trends in compound extremes

Compared with the mid-twentieth century, compound hot–dry extremes during maize-growing, wheat-growing, soy-growing and rice-growing seasons have increased[6,97]. In particular, since approximately the 1950s, the global frequency of such events has roughly doubled[7,98], with especially large increases in China[98]. Over the same period, the mean annual cropland area exposure to such events has increased by 1–2% per decade[6] relatively evenly across major breadbaskets. However, the most intensively cropped mid-latitude regions of North America and Southeast South America have experienced relatively little increase (or even a decrease) in hot–dry extremes[97], possibly as a result of natural climate variability[6], increased irrigation and cropland intensification[67], or both. Positive trends in hot–dry events have accelerated since approximately the 1980s and are largely attributable to warming temperatures more so than changes in precipitation[7,99].

Compound hot–wet events have also increased in frequency. Compared with the mid-twentieth century, the probability of compound flood and heat events has increased globally by roughly a factor of 2–3 (ref.[98]), including by a factor of 5–10 in much of China[100]. Indeed, the temporal clustering of extreme heat and rainfall days has increased by 2.5% per decade in China[65], but such trends remain poorly quantified on a global scale. Since 1979, extreme humid heat events have also doubled in frequency[101] and intensified[64], including over most cropping regions.

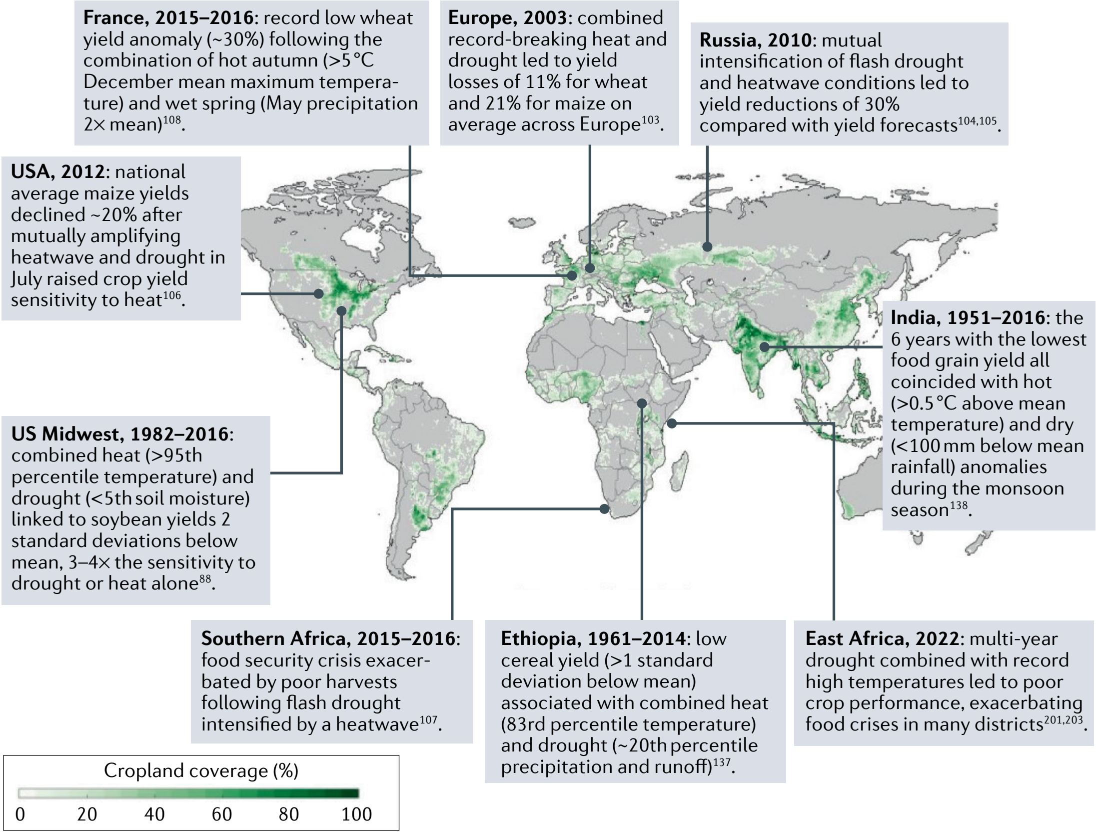
Yield consequences of rising compound extremes

Since 2000, several specific cases of compound heat and moisture extremes have been linked to severe yield losses (Fig. 4). Concurrent hot–dry anomalies predominate across continental Eurasia, North America and Southeast Africa, transition zones between energy-limited and water-limited environments[57] in which land–atmosphere coupling is strong[13,48,102]. For example, following the 2003 European heatwave and drought, wheat and maize yields dropped by 11% and 21%, respectively[103]. Similarly, grain yields declined by 30% after heat–moisture couplings amplified drought and extreme heat over the breadbasket in Russia in 2010 (refs.[104,105]). In 2012, the combination of severe heat and drought enhanced the heat sensitivity of maize and wheat in the US Great Plains[106], with maize yields declining by ~20% compared with the national average[90]. The 2015–2016 southern Africa food security crisis was also worsened by flash drought intensified by heatwaves[107]. The French wheat yields were unexpectedly reduced by 30% in 2016 after the combination of a wet autumn followed by a spring heatwave, a possibility missed by national yield forecasters[108]. These events primarily affect yields of largely rainfed crops (maize and soy) more strongly than widely irrigated crops (rice)[57].

Despite some evidence for rising impacts of warm droughts on crop photosynthesis since the 1980s[109], the impact of rising trends in compound extremes on global crop yields overall remains underexamined. In some areas, climate trends explain increases in year-to-year yield variability since the 1980s (Europe, China and East Africa for maize and Europe, Australia and Southeast South America for wheat)[110]. Meanwhile, the yield impacts of heatwaves or droughts have increased in Europe[111] and the USA[112] since the late twentieth century. Increasing compounding among various climate influences on crop yield has probably contributed to these changes, but exactly how and to what extent are not well quantified.

Future projections

Compound extremes are projected to continue intensifying under a wide range of plausible future emissions scenarios[5]. Understanding the implications of these changes for global crop yields is in its infancy and subject to considerable uncertainties. Nevertheless, consensus is emerging over certain dimensions of yield risk and opportunity from compound extremes. These risks and opportunities will largely be determined by responses of the three modes of compounding (crop-physiological, heat–moisture and crop–atmosphere interactions), as discussed subsequently.



France, 2015–2016: record low wheat yield anomaly (~30%) following the combination of hot autumn (>5 °C December mean maximum temperature) and wet spring (May precipitation 2× mean)[108].

Europe, 2003: combined record-breaking heat and drought led to yield losses of 11% for wheat and 21% for maize on average across Europe[103].

Russia, 2010: mutual intensification of flash drought and heatwave conditions led to yield reductions of 30% compared with yield forecasts[104,105].

USA, 2012: national average maize yields declined ~20% after mutually amplifying heatwave and drought in July raised crop yield sensitivity to heat[106].

India, 1951–2016: the 6 years with the lowest food grain yield all coincided with hot (>0.5 °C above mean temperature) and dry (<100 mm below mean rainfall) anomalies during the monsoon season[138].

US Midwest, 1982–2016: combined heat (>95th percentile temperature) and drought (<5th soil moisture) linked to soybean yields 2 standard deviations below mean, 3–4× the sensitivity to drought or heat alone[88].

Southern Africa, 2015–2016: food security crisis exacerbated by poor harvests following flash drought intensified by a heatwave[107].

Ethiopia, 1961–2014: low cereal yield (>1 standard deviation below mean) associated with combined heat (83rd percentile temperature) and drought (~20th percentile precipitation and runoff)[137].

East Africa, 2022: multi-year drought combined with record high temperatures led to poor crop performance, exacerbating food crises in many districts[201,203].

Fig. 4 | Crop impacts of major compound heat and moisture extremes. Select examples of compound heat and moisture extremes and their resulting crop yield impacts. Shading depicts global cropland area density (percentage of grid cells covered). Among the various forms of compound heat and moisture extremes, hot drought events are the leading cause of poor harvests and represent the majority of research efforts. Background map adapted from ref.[219] under a Creative Commons licence CC BY 4.0.

Crop-physiological interactions under climate change

Crop-physiological responses to compound extremes will be shaped by responses to long-term change in individual climate variables. Mean and extreme high temperatures are projected to continue warming in the coming decades with relatively high confidence[113,114]. Projected changes in mean precipitation[96], runoff[115], aridity[116] and drought[18] are, by contrast, uncertain across many important cropping regions. Short-duration precipitation events are, nevertheless, robustly expected to intensify globally[21], accompanied by longer dry spells. Beyond altering the likelihood of compound heat and moisture extremes (Fig. 2d–f), the combination of these changes will affect crop-physiological interactions and alter the timing and pace of crop development and growth stages (Fig. 5). Mean changes in climate will not only directly affect yield but also alter crop phenology and exposure to compound extremes, influencing their acclimation to various stresses.

Crop yields are often projected on the basis of mean warming in ways that might be unreliable because of the three modes of compounding. Using a range of methods, temperature-based yield projections indicate global average reductions of ~10% by the late twenty-first century[117]. Empirical yield sensitivities capture historical impacts of both heat and its tendency to co-occur with low soil moisture at seasonal or shorter timescales. However, changes in the hydrological cycle with warming are complex and uncertain in many regions[96]. Extrapolating empirical temperature sensitivities over decades conflates temperature and moisture effects and thus probably overestimates future impacts. Projections considering temperature, moisture variables and their interactions indicate considerable modulation of warming-only yield impacts by changes in moisture and compound extremes. However, there is little consensus on whether aspects of this modulation will exacerbate[57,108], alleviate[85,118] or have little net effect[84,119] on the impacts of warming. Yield projections specifically and holistically accounting for the impacts of increasing compound extremes are presently lacking.

Cropping seasons and agroecological zones will probably shift as climates change and farmers adapt[120], altering the timing of compound extremes relative to crop calendars. In cooler climates, moderate warming alone can lead to potential yield gains (especially for wheat[121]) owing to longer growing seasons, adoption of slower-maturing cultivars and/or additional harvests per year (multiple cropping)[122]. However, warmer temperatures will hasten crop development, grain filling and senescence, reducing yields[123,124] (Fig. 5). Beyond yield potential, such phenology changes will alter the timing of crop water demand and climate-sensitive growth stages relative to shifting climatologies of extremes (Fig. 5). For winter wheat, yield benefits from avoided heat stress due to earlier flowering are projected to balance yield losses from faster development[125]. However, whether such compensations apply for heat combined with drought or excess moisture[126] stresses, and whether earlier sowing of slower-maturing crops is sufficient to avoid peak warm-season heat and aridity, remain uncertain.

Acclimation of crop morphology and metabolism to earlier climate stress further influence susceptibility and cross-tolerance to subsequent stress[42,127] (Fig. 5). For example, expansion of leaf area in response to heat or root biomass accumulation under drought could establish architectural tolerance to repeat exposure to heat or drought stress[123]. Meanwhile, early excess moisture extremes might diminish root development[35] and impede subsequent drought tolerance. These acclimations to univariate extremes could variously confer cross-tolerance, or enhance susceptibility, to sequences or combinations of stresses[47,128].

A critical uncertainty for future crops is the net effect of physiological yield benefits and climatic yield risks from higher CO_2 (refs.[121,129]). With higher CO_2, many crops photosynthesize more per unit water lost, but are simultaneously exposed to a more extreme climate[130,131]. Higher CO_2 can further diminish the nutritional value of crops[132]. Rising CO_2 will probably alter the links between yield and the exchange of water and heat between land and atmosphere[10,133], and so is relevant to future crop impacts of compound extremes. For instance, greater crop water-use efficiency could limit the ability of crops to thermoregulate through transpiration[134], potentially amplifying local heat extremes and impacts[135], especially during drought[136].

Joint changes in moisture and heat conditions across timescales can alter yield sensitivities to climate variables when compared with the historical period, leading to accumulating or offsetting impacts across the course of a growing season. Whether these compounding effects will present risks or benefits on average to crop yields remains critically uncertain. There is growing evidence, however, that traction on this question will require a consideration of compound climate extremes and changes.

Compound extremes under changing heat–moisture interactions

Changes in univariate extremes under climate warming can increase the likelihood of compound extremes by chance alone. For instance, warming increases concurrent heat–drought events because droughts are simply warmer on average[62], even where total precipitation remains constant or increases[137,138] (Fig. 2d). Nevertheless, the frequency of hot–dry extremes during the warm season is projected to rise most strongly where precipitation is expected to decrease[139], such as in Mediterranean climates, southern Africa, coastal West Africa, southern Europe and northern South America[140,141]. However, changes in heat–moisture interactions could further affect the frequency and intensity of future compound extremes. Evolving land–atmosphere interactions and links among heat, humidity and rainfall will probably affect the future occurrence of hot–dry and hot–wet compound extremes.

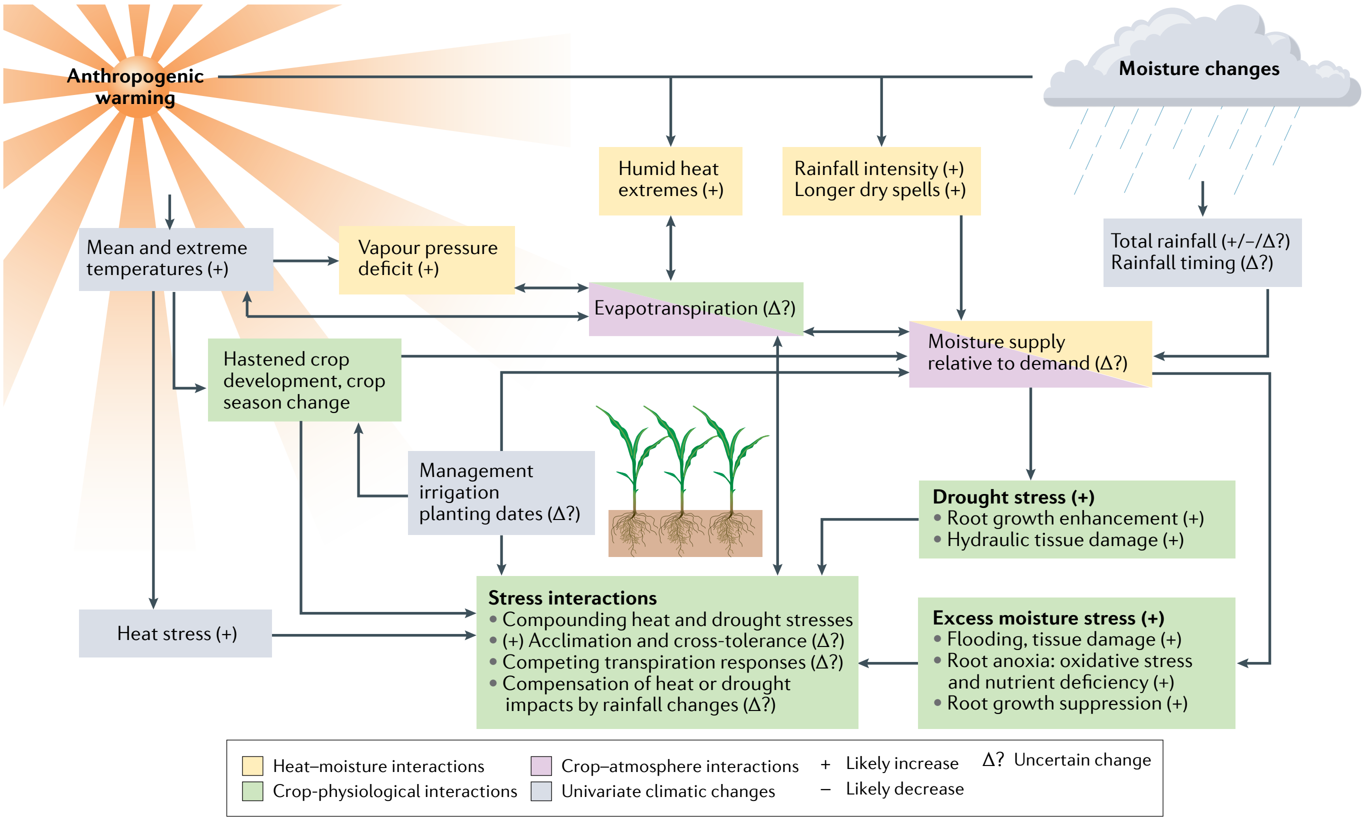


Fig. 5 | Changing compound extremes and modes of compounding under climate warming. Key changes in climate variables and crop consequences, expressed as likely increases, decreases or uncertain responses. Coloured boxes represent the modes of compounding while grey boxes represent management or univariate climatic changes. Arrows denote causal links and interactions among climatic changes and their crop impacts. Double-headed arrows indicate bidirectional causality. In their roles as both climate events and crop stressors, drought, extreme heat and excess moisture interact in complex and diverse ways. The ultimate yield impacts of climate warming will depend on these interactions and compounding effects, many of which remain uncertain.

Owing to increased evaporative demand and drier surfaces and root zones[96] (Fig. 2e), present-day land–atmosphere interactions are expected to strengthen under warming, enhancing compound hot–dry events, especially in transitional zones. For example, under a high emissions scenario by the late twenty-first century, globally averaged joint hot–dry extremes are projected to intensify in the warm season by 20–30%[142], and become twice as likely[48], because of changing heat–moisture interactions (Fig. 2f). These changes are beyond those expected from warming alone. Furthermore, some presently humid crop regions (such as northern Europe) are projected to become more transitional, boosting heat–drought concurrence[48]. In many humid regions where land–atmosphere interactions are not projected to change substantially overall, climate change might strengthen land–atmosphere interactions specifically during droughts, resulting in amplified warming of extremely dry days[143]. The influence of natural vegetation on land–atmosphere interactions and compound extremes will probably shift as higher atmospheric CO_2 concentrations alter vegetation physiology[133,144]. However, the magnitude and direction[115,145] of these changes are actively debated.

Heat–moisture interactions in a warmer climate will also probably raise the occurrence of both dry and wet extremes within crop-growing seasons (Fig. 5). Short-duration rainfall events are robustly expected to intensify at or above the Clausius–Clapeyron scaling rate (≥7% per degree Celsius), outpacing changes in seasonal total precipitation (+~2% per degree Celsius on a global average)[21,146]. This difference in rainfall change factors at different timescales implies that rainfall will become concentrated into fewer, heavier events and that precipitation frequency will decrease overall[147]. Future crops will thus be exposed to heavier downpours separated by longer dry spells, with interacting impacts on crops across the growing season (Fig. 5).

Paradoxically, the climatic connections between heat and moisture enhance drought and excess moisture stresses within an average growing season. However, the crop yield implications of these rainfall intensity and frequency changes across timescales remain uncertain. For instance, under 1–2 °C additional warming in the USA, the occurrence of yield-benefitting heavy hourly rainfall is projected to increase, whereas yield-damaging hourly extremes remain rare, resulting in 2–3% net maize and soy yield gains[118]. Conversely, daily rainfall intensification is projected to decrease yields in the USA and India owing to the lower number of rainy days during the growing season, even if total growing season precipitation remains constant or increases[148,149]. The opposite is true in semi-arid West Africa, where increased daily rainfall intensity benefits sorghum yields in crop models[150].

Future changes in the coincidence of extreme heat and heavy rainfall could have further implications for compound climate impacts on crops. During the growing season in many temperate and sub-tropical areas, short-duration rainfall extremes are more likely on hot days as rainfall intensities increase with temperature on hourly to daily scales[21]. With continued warming, future extreme heat and precipitation could become increasingly concurrent[62]. However, the understanding of compounding or compensating impacts of concurrent heat and rainfall extremes on crop yields is limited (Fig. 5).

On average, relative humidity is projected to decrease over land with climate warming[151]. However, extreme humid heat events are also projected to strongly increase in frequency, duration and intensity in most crop regions[152,153]. If future heatwaves are more likely to co-occur with high humidity, their indirect moisture-related impacts on crops might be reduced when compared with historical heatwaves. High relative humidity could limit water loss during extreme heat, but might potentially also limit the ability of crops to thermoregulate through transpiration. The strong historical correlation of temperature with humidity[154] and VPD[10] poses a considerable challenge in disentangling direct thermal and indirect moisture impacts of high temperatures to robustly examine this potential on large spatial scales[10]. Increasing humid heat extremes will also pose a mounting health hazard to agricultural workers[155].

Although consensus is emerging on the future of compound extremes, explicit climate-model projections of compound extremes are in their infancy and subject to limitations and uncertainties. Climate models generally simulate historical trends in compound hot–dry[156,157] and hot–wet[98] events reliably. However, certain underlying processes that drive compound extremes are subject to important modelling uncertainties, particularly regarding future change in aridity[20], land–atmosphere interactions[142], natural vegetation[115] and precipitation[158].

Potential limits to beneficial crop–atmosphere feedbacks

Cropland extent and crop yields have increased markedly in many regions during the twentieth century[159], meaningfully altering land-surface properties[59]. Observational[160] and climate model[69] analyses suggest that these trends cooled and moistened important crop regions, notably in the USA, China and India. These effects have been attributed to enhanced evapotranspiration and latent heat flux, either from increased crop photosynthesis and water use[161] or expanding irrigation[82,162].

Increasingly productive crops preferentially cool detrimental heat extremes, masking the harmful component of anthropogenic warming[66,67]. This suppression of extreme heat is claimed to have contributed importantly to yield growth (for instance, 17–28% since 1981 for US maize[163]) via a proposed ‘crop–climate feedback’, in which cooler maximum temperatures induced by technological yield trends generate additional yield gains and cooling. This feedback is consistent with the reported cessation of crop-related cooling of heat extremes during droughts[164], which can prevent crops from buffering heat extremes by transpiring, and might explain an uptick since the late twentieth century in US maize and Indian wheat yield sensitivity to drought[112,165].

The mutual influence of yield and climate trends in some densely cropped regions can be usefully considered a form of compound climate event, which has historically benefitted average crop yields. However, future agricultural risks from crop-driven cooling are also identified. For example, a slowdown or reversal of yield growth could weaken the cooling effect of crops[166], leaving them more exposed to ongoing warming[160,163,167]. Further, crop–atmosphere interactions might amplify future yield variability[168,169] by widening the yield difference between dry and optimal conditions. It is unclear whether this effect would be limited or enhanced by plant physiological responses to higher atmospheric CO_2, which might reduce transpiration but conserve soil moisture[130].

Water availability and sustainability

Managing available freshwater resources — including snowmelt, surface runoff and groundwater — is an integral means of reducing water stress to stabilize crop yields. Currently, irrigation increases maize and wheat yields by ~20–30%[170] and reduces the effects of climate extremes on crop yields[3,165]. Irrigation directly alleviates moisture stress during drought conditions and decouples temperature and moisture stress at the land surface and in plants. By providing accessible water for crops to use in transpiration during heat extremes, leaf and canopy temperatures can be as much as 10 °C lower than air temperature in the presence of irrigation[70,71].

Irrigation water use in the present climate is constrained by the availability of freshwater as well as institutional and economic factors[171]. Climate change is projected to reduce freshwater available for irrigation in some regions owing to declining runoff[96] and snowmelt[172,173]. This outcome could threaten existing irrigation-dependent production systems in the western USA, Southwest South America, northern China and Central and High-Mountain Asia[174]. Improved and expanded water management, however, could sustainably increase irrigated agriculture and food production in a warming environment[175,176].

In regions where climate change makes droughts more frequent and intense, groundwater is likely to be an increasingly important source of irrigation water. Most groundwater aquifers around the world are being used sustainably[177]. However, agriculturally important aquifers in China, India, the Middle East and North America are being used faster than they can be replenished by natural recharge rates[177], threatening crop production[178]. As evaporative demand rises with warming, increased farmer reliance on groundwater[179] and decreased recharge rates put further pressure on aquifers[180]. The key challenge will be to strategically develop groundwater irrigation and use it sustainably over the long term, so that it is available to use during critical droughts and compound extremes.

Should irrigated croplands revert to rainfed management conditions because of reduced water availability or economic and institutional factors, it is likely that these croplands would suffer yield declines. These declines would occur as a result of increased moisture stress during dry years[181] and a reduction of irrigation-induced cooling, increasing the incidence of hot–dry extremes. This possibility would be especially concerning in regions that are likely to experience declining soil moisture[96], decreased runoff[115] and reduced snowmelt[172], such as western North America, parts of Central Asia, southern Africa and Southwest South America.

Although it is expected that intensifying drought and heat will diminish or eliminate the benefits of increased atmospheric CO_2 to crop yields in some regions[130], the effect of CO_2 on water fluxes is more uncertain. By increasing water-use efficiency under higher CO_2, crops would reduce their water consumption, leaving more freshwater available for other uses such as irrigation[129]. In the mid-latitudes, however, it is also possible that a longer growing season and increased atmospheric water demand increase crop water consumption and decrease freshwater availability[115].

Implications for adaptation

The nature of compound extremes presents unique challenges for climate adaptation in crop production. Adaptations implemented to cope with one type of climate extreme might reduce crop or food system resilience to other types or combinations of extremes. As such, compound extremes raise new risks of agricultural maladaptation, an emerging risk factor emphasized in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[182]. With increasingly concurrent climate stresses, adaptation avenues will need to increasingly target robust cross-tolerance and to avoid antagonisms between pathways of resilience[183]. The effectiveness and limitations of crop adaptation avenues for compound extremes are discussed subsequently.

Adaptation avenues for compound extremes

It is critical to pair detailed knowledge of compound climate extreme typologies with an evaluation of adaptation avenues, their efficacy under various combinations of stresses as well as their sustainability co-benefits or trade-offs. Such information aids in identifying adaptation strategies that enhance the resilience of crop production to combinations of climatic stresses[184], as well as benefitting other goals (such as productivity, natural resource use, nutritional quality and climate change mitigation)[185]. To this end, a suite of adaptation strategies exists to enable flexibility in coping with compound climate extremes at diverse spatial (farm to inter-regional) and temporal (daily to decadal) scales (Table 1).

Adaptations aimed at crop biophysical and management responses advance overall climate change adaptation while attenuating the effects of some compound extremes. These interventions include adapting sowing dates[120]; adopting new[186], improved (slower maturing and better adapted)[187] and/or diversified[188] crop species or varieties; and expanding and optimizing irrigation[175,176] and soil water management[160]. Such adaptation avenues operate at plant-to-farm levels, but can be supported by policies at regional scales. Although many of these interventions have been explored for crop adaptation to climate change in general[189], the understanding of their efficacy for compound extremes is budding.

Antagonisms between heat and drought breeding strategies provide an example of the unique challenges of compound extremes for adaptation. Breeding a drought-tolerant crop by raising its water-use efficiency (for instance, through stricter stomatal regulation) decreases the ability of the crop to thermoregulate by transpiring[44]. This approach strengthens crop–atmosphere interactions and worsens compound climate impacts on yields. However, soybean can maintain flower transpiration, whereas leaf stomates close during combined heat and drought, relatively cooling the heat-sensitive flowers by 2–3 °C[72]. Such physiological responses illustrate the diverse genetic potential for new breeding targets to maintain sufficient and stable yields under compound stresses[183].

Certain adaptive management techniques further enhance adaptation to increasingly compound extremes. For instance, increasing soil organic carbon improves the ability of soil to absorb heavier rainfall and retain it during dry spells[190]. If effectively implemented, this avenue can limit the negative impacts of both dry and wet extremes, and harness potentially beneficial aspects of joint heat and moisture changes for crops, with additional carbon sequestration co-benefits.

Many current policy incentives and breeding lines are geared towards increasing the average yields of crops, rather than increasing the climate resilience or tolerance of crops. However, higher yields often make the crop less resilient[112,165], partly owing to worsened compounding of yield impacts from enhanced crop–atmosphere interactions[164]. Increasing compound extremes probably necessitate more holistic crop adaptation goals. Other agri-food system actors use a host of strategies to support adaptation to compound extremes at larger spatial scales[191,192]. These interventions include supporting ecosystem services provided by non-agricultural land in cropping regions[193] and instituting effective insurance programmes[194,195] and early-warning systems[196] (Table 1).

Many adaptation measures feature not only potential effectiveness for compound extremes but also limitations (Table 1). With coordinated planning that accounts for diverse and increasingly compound extremes, these strategies can be used in combination to form compound climate 'adaptation portfolios' to compensate for the shortcomings of any individual strategy (such as losses in income or yield from adopting resilient varieties) and better equip stakeholders to successfully navigate compound climate extremes[184].

Making science useful in the face of compound extremes

Scientific advances in understanding compound extremes and their impacts on cropping systems are occurring alongside rising and urgent demand to predict them for appropriate adaptation, mitigation and

Table 1 | Agricultural adaptation avenues for compound extremes

Adaptation avenue	Spatial scale	Temporal scale	Description	Effectiveness	Limitations	Ref.
Management interventions						
Sowing dates	Farm to regional	Sub-seasonal	Modified sowing dates to avoid peak stress, take advantage of longer growing season	Avoid moments of concurrent heat, drought and extreme rainfall	Insufficient growing-season window to avoid peak combined stress periods, limits to field workability from spring moisture extremes	120
Irrigation	Farm to regional	Daily to decadal	Sufficient, timely and efficient applications of water	Joint reduction in heat and drought exposure and impact	Surface water availability during drought, declining groundwater	165
Precision agriculture	Farm	Daily to sub-seasonal	Data-driven tailoring of management and fertilization to field heterogeneity	Optimize input applications for combined stress resilience	Challenges of scalability	213
Crop varieties and genetics						
Crop switching	Farm to inter-regional	Seasonal to decadal	Adopt existing crops or cultivars with combined stress resistance or resilience, earlier or slower maturation	Drought and heat-tolerant species (sorghum and millet) already widely grown	Issues of marketability of alternative crops, fundamental limits to stress tolerance	186
Crop improvement	Regional to inter-regional	Decadal	Add genetic resistance and resilience to combined stress, adaptive phenology to avoid peak stress	Some stress resistance pathways confer cross-tolerance to combined stress	Need to avoid physiological antagonisms between stress resistance pathways	187
Crop diversification	Farm to regional	Sub-seasonal to decadal	Plant a larger variety of crops within a single season, or institute more diverse crop rotations	Yield risk distributed across many crops with complementary stress resistances	Challenges with managing and marketing diversified crops, lessened economies of scale	188
Soil characteristics						
Soil characteristics	Farm	Annual to decadal	Enhance soil organic carbon, reduced tillage	Optimize absorption of water from heavier rainfall, enhance retention during dry spells	Improve water retention without impeding drainage	190
Institutional food-system strategies						
Ecosystem services	Farm to regional	Annual to decadal	Protect and bolster naturally vegetated ecosystems within or surrounding cropping regions	Land-surface cooling, water retention and flood control by natural vegetation	Joint susceptibility of crops and natural vegetation to compound extremes	193
Crop insurance	Regional	Annual	Protect farmer income from climate shocks	Farmer resilience to compound extreme impacts	Potential encouragement of maladaptive practices such as unsustainable irrigation	195
Early-warning systems	Regional to inter-regional	Annual to decadal	Predict and communicate concurrent extreme risk	Available and useable climate information to adapt crop choice and management planning to forecasted compound extremes	Science–practice divide, limits to climate predictability on practical time horizon	196
Markets and distribution	Regional to inter-regional	Decadal	Develop markets for new crops, market resilience to shocks, emergency food relief	Improved and equitable food distribution during crop failures, market demand to support uptake of new crops	Food import dependence can lead to food system vulnerability, barriers to trade can exacerbate food shocks	192

production optimization[197]. Robust understanding of heat–moisture, crop-physiological and crop–atmosphere interactions is needed to reliably project future compound extremes and inform adaptation strategies. However, agricultural climate impact sciences are associated with large uncertainties[121], often even larger than those related to projected changes in climate and compound extremes[121,198], which complicate immediate policy action and sometimes slow implementation.

The emerging evidence base on compound extremes can be increasingly incorporated into risk assessments at various spatial and temporal scales relevant for cropping systems. However, this information must be used within appropriate frameworks for decision-making. Further, such frameworks need to accurately and rigorously consider the uncertainties and limitations in predicting compound extremes[199] and estimates for their crop damage[200]. Existing frameworks such the Famine Early Warning System[196,201] or the GEOGLAM Crop Monitor[202,203], which already include information on climate extremes such as drought into early-warning forecasts of crop production shortfalls and food security, could serve as important models and entry points for incorporating the latest science on compound extremes and their agricultural impacts.

Despite the emerging efforts and opportunities to incorporate the latest compound extremes science into agricultural decision-making,

Glossary

Clausius–Clapeyron relation	How the water-holding capacity (saturation vapour pressure) of air increases quasi-exponentially with temperature, with implications for both precipitation (water supplied to clouds) and drought (water removed from land).
Convection	The rising motion of buoyant warm and/or humid air, leading to cooling of the air, condensation of water vapour and eventually precipitation. A common cause of extreme rainfall.
Crop physiology	The biological processes governing the growth, development and reproduction of crop plants, many of which are connected to climate.
Crop yields	Crop productivity on an area basis (mass of harvested crop per unit harvested area).
Drought	Extended periods of high vapour pressure deficit, or deficient precipitation, soil moisture or surface water. Diverse definitions exist across disciplines, sectors and systems.
Evapotranspiration	The vaporization of water into the atmosphere from the land surface (evaporation) and plants (transpiration) combined. As an endothermic reaction, evapotranspiration also transfers latent heat between land and atmosphere.
Land–atmosphere interactions	The modulation of boundary layer climate by feedbacks with the land surface involving diverse processes, linking the energy and water cycles.
Latent heating	The flux of heat from the land surface to the atmosphere due to evapotranspiration, transferring potential energy to overlying air in the form of water vapour without changing the air temperature.
Sensible heating	The flux of heat from the land surface to the atmosphere leading to a change in air temperature.
Stomata	Closable leaf pores that regulate the uptake of carbon dioxide and coincident loss of water (transpiration), exerting an important influence on energy, water and carbon exchanges between land and atmosphere.
Transitional zones	Regions with intermediate average soil moisture (neither arid nor humid), typically featuring strong land–atmosphere interactions.
Univariate extremes	Climate events with extremes of a single climate variable (such as temperature).
Vapour pressure deficit	(VPD). The difference in water vapour content of air between actual and saturated conditions, acting as a force drawing water from within plants, where air is saturated, towards the typically drier atmosphere.

several outstanding limitations and constraints on making adaptation successful exist. Importantly, the current western research and development paradigm is still the dominant mode of knowledge production in global agriculture. Such approaches focus chiefly on univariate climate risks and genome-centric technology trends for a few crops and cropping systems, whereas compound extremes necessitate holistic, integrated, systems-based approaches. Moreover, scientific observations and research relating compound extremes to agriculture are skewed towards industrialized countries that often have access to larger amounts of agricultural statistics and research funding. As a result, knowledge about the occurrence and prevalence of compound extremes and their impacts on agriculture in other regions is limited[189,204]. Efforts have been underway to explicitly address the combined risks of heat and drought in crop improvement, such as wheat via the Heat and Drought Wheat Improvement Consortium[205]. However, more site and climate-responsive adaptation could be achieved if these technological improvements were combined with other knowledge production systems (such as local and regional traditional agroecological or indigenous knowledge) that include more diversified farming approaches[206].

Disconnects among science, policy and field-level practice also remain, limiting adaptation to compound extremes. For example, farmers obtain information from various sources including their own social networks[207], and knowledge that is relegated to academic journals or even experimental or demonstration plots might not be readily acted on. In addition, disconnects exist between biophysical evaluations of adaptation options and considerations of the actual costs of implementation, the capacity of individual farmers to adopt these methods and even the perceived benefits and legitimacy of the options being promoted[189]. For instance, making modern hybrid breeds available to farmers in lower-income countries is a persistent challenge[208]. Furthermore, much of the research funding to investigate impacts of climate extremes on agriculture focuses on heat and/or drought stress, to the detriment of other important, and potentially compound, climate risks that farmers face (notably, excessive moisture)[32,118,209].

Adaptation beyond field-level agronomic interventions could be necessary when farm-level resilience is exceeded. Compound extremes science can be more deeply integrated into new or redesigned insurance policies and products[194,200,210], and into investments in income stabilization[210] and other in-kind support such as the dissemination of seeds and fertilizers following an extreme event. These risk reduction approaches might influence the decisions of farmers to invest in adaptive technologies and management options[210]. However, the availability of crop insurance does not always result in the adoption of climate-smart, conservation management practices[211,212], and alternative management strategies (such as crop diversification[194] or precision agriculture techniques[213]) might preferred to loss-limiting policies like crop insurance. Furthermore, the availability of crop insurance, and even research at the intersection of climate change and crop insurance, is largely still limited to industrialized, high-income countries[194]. Additional work is needed to develop and scale cost-effective financial support for farmers facing various compound extremes in diverse regional contexts.

Understanding and measuring the efficacy of crop adaptation options, and coordinating their adoption and scaling, remain challenging. For example, observations show that farmers advance planting dates for spring crops in temperate regions[120], but cohesive knowledge is lacking on this decision-making process, which is largely uncoordinated at an institutional level. Information on how farmers choose crop cultivars or management activities to mitigate climate and compound extreme risks is even less well documented and understood[214]. Such forms of 'autonomous', farmer-led adaptation are usually unaccounted for in current climate-crop models, further limiting the accuracy and realism of future crop impact projections.

Summary and future perspectives

Compound heat and moisture extremes constitute a specific and mounting set of hazards to global crop yields. Joint hot–wet and hot–dry extremes have increased in frequency, severity and extent since the mid-twentieth century and have been linked to historical poor harvests in many regions (Fig. 4). At the same time, compound extremes provide a lens for understanding the effects of climate on crops more generally. Three modes exist through which the influence of climate on crops can become compounded (Fig. 1). These include interactions among crop-physiological responses to different aspects of climate leading to compound impacts, heat–moisture interactions in the climate system leading to compound hazards and crop–atmosphere interactions through which hazards and crop impacts can mutually compound. Advances in data, modelling and analysis of these modes have led to new conceptualizations of how climate affects crop yield, improving the reliability of projections of future climate risks to global agriculture.

Although the lens of compound extremes has added nuanced understanding of how climate impacts crops, each mode of compounding is presently associated with important uncertainties (Fig. 5). The interactive effects of combined heat and drought on crop physiology at molecular-to-canopy scales are only beginning to be dissected, and the potential for compensating or exacerbating crop impacts of increasing combinations of wet extremes with dry and/or hot extremes is scarcely researched. One priority is to develop yield projections holistically, accounting for simultaneous rainfall and dry-day changes across sub-daily to seasonal timescales. Furthermore, experimental research is needed to assess how climate stress acclimation will confer cross-tolerance or enhance susceptibility to sequences or combinations of stresses and build these insights into crop models to improve projections.

Observational and modelling uncertainties also limit the projection of future compound extremes (Fig. 5). Earth system models used to project future climates disagree substantially on future changes in key heat–moisture interactions, especially because of differing simulations of vegetation, soil moisture and land–atmosphere interactions. Projections of future crop–atmosphere interactions can be improved through more complete representation of crops in climate models and of relevant climate interactions in crop models. To do so, experimental insights are needed into key uncertainties such as crop responses to excess moisture and the countervailing influences of rising atmospheric CO_2.

These uncertainties have been previously highlighted as disciplinary priorities. However, greater integration of methods and findings across research communities will help to translate emerging understanding into the insights needed to anticipate and adapt to the impacts of compound extremes on crops. Synergies between experimentation, climate modelling and statistical and process-based crop modelling remain underutilized. In particular, new statistical and modelling approaches can help to assimilate results at differing spatial and temporal scales. Furthermore, greater consistency and harmonization of the diverse compound extreme metrics applied in crop and climate research will most likely speed the translation of modelling and theoretical advances into adaptation-relevant results (Box 1).

The biophysical impacts of compound extremes on crops comprise a complex, interdisciplinary scientific question. However, these impacts will be felt by the diverse actors in the wider food system. Although the focus of this Review is biophysical, we also address how these insights can inform wider food system adaptation necessary for twenty-first-century food security. Greater focus on regional staples (such as tubers and millets) and global non-staple crops (such as fruits and vegetables) is essential to extend compound extremes insights to the wider food production basket. Additional research is also needed to understand how the impacts of compound extremes on yield could cascade to subsequent steps in food supply chains and interact with other environmental, political and economic risks.

Consideration of compound extremes reveals unique adaptation challenges and potentially some opportunities. Dedicated research efforts will be needed to capture the effectiveness of promising crop and food system adaptation avenues for compound extremes, while minimizing their drawbacks (Table 1). In highlighting emerging consensuses and persistent uncertainties, this Review takes stock of the state of the science and the open questions. We also highlight some challenges and promising avenues to bridging the research–practice divide, which will be essential to translate science into robust adaptation.

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All authors contributed to discussions, writing and reviewing of the manuscript. C.L. coordinated the writing and led the figure contributions. C.L. and W.A. conceived the main structure of the manuscript.

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The authors declare no competing interests.

Additional information

Correspondence should be addressed to Corey Lesk.

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[1]Lamont-Doherty Earth Observatory, Palisades, NY, USA. [2]Neukom Institute for Computational Science, Dartmouth College, Hanover, NH, USA. [3]Department of Geography, Dartmouth College, Hanover, NH, USA. [4]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA. [5]NASA Goddard Space Flight Center, Greenbelt, MD, USA. [6]Department of Earth System Science, University of California Irvine, Irvine, CA, USA. [7]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, USA. [8]School of Environmental and Rural Science, University of New England, Armidale, NSW, Australia. [9]NASA Goddard Institute for Space Studies, New York, NY, USA. [10]Center for Climate Systems Research, Columbia University, New York, NY, USA. [11]Potsdam Institute for Climate Impacts Research (PIK), Member of the Leibniz Association, Potsdam, Germany. [12]Department of Environmental Studies, New York University, New York, NY, USA. [13]Department of Geography and Spatial Sciences, University of Delaware, Newark, DE, USA. [14]Department of Plant and Soil Sciences, University of Delaware, Newark, DE, USA. [15]Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA.