Climate Risk Management 34 (2021) 100378

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Climate risk to agriculture: A synthesis to define different types of critical moments

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ARTICLE INFO

Keywords:
Climate variability
Compound risk
Crop stage
Indirect impact
Coping
Adaptation
Critical moment
Climate services

ABSTRACT

Increasing climate variability will put crop production at risk, undermining the sustainability of agriculture-based livelihoods. Much effort has gone into assessing differential vulnerability – or who is at risk. However, the time dimension of increased risk – the when – is often only implicitly included in modelling, statistical and empirical studies. We define and explore the concept of "critical moments" (CMs); that is, periods of heightened risk during the year when farm households are vulnerable to specific climate hazards. The climate modelling, agronomy and socio-economics literature is reviewed to define different types of critical moments. Climate modelling emphasizes hazards but is less specific about the time window of risks in relation to crop cycles. Agronomy research develops cause-and-effect relationships between weather variables and yields by crop stage but generally does not consider hazard frequency and associated vulnerability. Socio-economic research analyses associations between hazards, yields and farm income, but often lacks full process knowledge, neglecting other pathways that contribute to vulnerability. Our synthesis aims to bridge disciplinary silos, and proposes an integrated concept towards risk. In this study, three types of CM are identified: CM's with immediate, compound and shifted impact. The concept of critical moments is novel as it considers direct and indirect impacts as well coping strategies. Viewing climate risk to agriculture through a CM lens can support greater interdisciplinary engagement to identify vulnerabilities and develop and promote effective coping options and user-relevant support mechanisms to reduce vulnerabilities specific to particular places and moments.

1. Introduction

Global warming changes not only the climate's mean state but also its variability, which is projected to increase in most areas (Panday et al., 2015; Schär et al., 2004). Climate variability and extremes are a key driver behind rises in global hunger and one of the leading causes of severe food crises, particularly in the most food insecure regions (Richardson et al., 2018; WHO, 2018). A vast literature addresses the negative impacts of climate variability on agricultural production. Throughout the production season, crops are sensitive in varying degrees to different weather events. Both inter- and intra-annual rainfall variability, affects the outcome of

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https://doi.org/10.1016/j.crm.2021.100378
Received 1 November 2019; Received in revised form 30 October 2021; Accepted 31 October 2021
Available online 2 November 2021

cropping systems during any particular season (IPCC, 2012; Nippert et al., 2006). A sudden change in temperature at particular times in the growing season (Tripathi et al., 2016), or out-of-season spikes in humidity (Hall, 2017), hail (Singh et al., 2017) and wind (Gardiner et al., 2016) are examples of weather events that can impact crop development, yields, and farm income.

Academic and popular reporting on extreme weather and large-scale climate events – the disasters – tends to overwhelm the impacts of smaller intra-annual and localized hazards. Shifts in seasonal runoff, precipitation, humidity, and temperature regimes can be just as disruptive as larger, more dramatic weather events such as large scale floods (IPCC, 2012). Similarly, a weather event that is not statistically extreme in itself may have extreme impacts if a critical threshold is crossed over a critical crop stage, or a period when farmers have less capacity to cope (Seneviratne et al., 2012). Changing weather patterns, thus, threaten agricultural production and increase the vulnerability of most of the world's poor who depend on agriculture for their livelihood (Lipper et al., 2014).

The timing and interactions of stresses at different crop growth stages may cause higher losses and increase food insecurity in the future (Thornton et al., 2014). A growing literature addresses the role of the timing and severity of climate hazards, to identify the adaptation interventions required to improve resilience at the farm level (Heltberg et al., 2009; Wilby and Dessai, 2010). Weather hazards may also disrupt farm operations and field workability at crucial stages, affecting production costs in addition to impacting crop yields and quality. Even if farmers cope with a hazard, there may be a cost associated with these coping measures (Mandryk et al., 2017). Net farm income is affected by both change in yield and cost (Thamo et al., 2017). The level of risk to impact on net farm income is high if an adverse weather event coincides with a sensitive crop stage and other adverse effects such as higher incidence of weeds, diseases and workability issues that affect a farmer's capacity to cope are included (Shah et al., 2020; Toeglhofer et al., 2012).

Most climate change impact research has been confined to disciplinary silos, mostly either studying a hazard's probability or its effects on yields largely ignoring the impacts of coping and indirect effects. Adaptation tends to target impacts of changes in the mean climate and estimates on the benefits of adaptation mostly do not account for possible changes in climate variability, or in related condition such as local water resources availability (Burke and Emerick, 2016; Butler and Huybers, 2013). Impacts of hazards vary by location, agro-ecologies and cropping seasons, as do coping possibilities (Penalba and Elazegui, 2013). Even within a homogeneous production region, adaptation needs to be tailored to local conditions (Perry et al., 2020).

Considering the importance of the time dimension of hazards – and the likelihood of increased climate variability in the coming years – regarding the vulnerability of agricultural livelihoods, we introduce the concept of "critical moments" (CMs), which we define as periods of risk during the year when livelihoods are vulnerable to specific climate hazards. We elaborate on the concept of CM through a review of the literature focusing on the following key question: "When, within a crop production cycle, farming communities

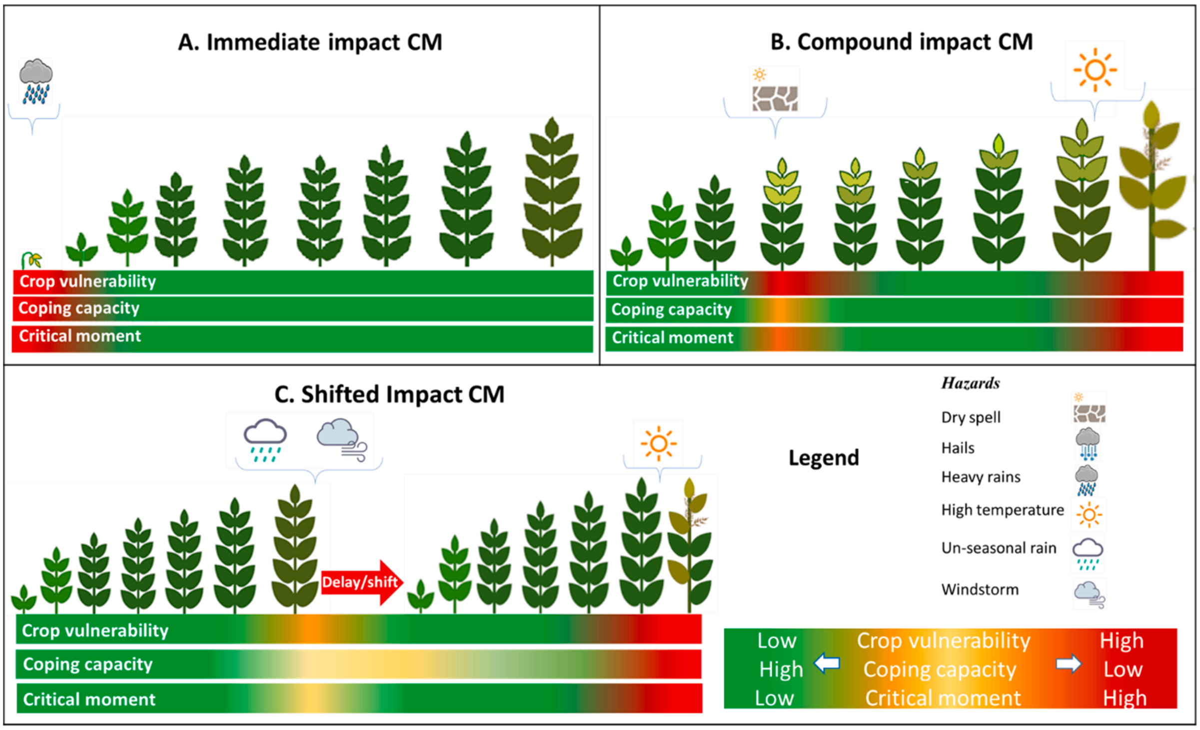

Fig. 1. Conceptual design of critical moments (CMs), illustrated over a cropping calendar with A. Immediate Impact CM arises from a hazard causing immediate crop/income loss; B. Compound Impact CM causes loss from multiple hazards over the same cropping season; C. Shifted Impact CM causes major loss over the next crop due to a hazard occurring during the later period of the previous crop, especially in a double cropping system. Hazards presented per crop stage are purely indicative, but are informed by hazards reported to be most common in wheat-based, multi-cropping systems in the Indo-Gangetic plain (Shah et al., 2020).

are most vulnerable to climate hazards?" Within the context of CMs, 'when' is not a single hazard incidence or crop phenology, but rather a multifaceted concept that encompasses the time window of risk, with respect to the occurrence of a climate hazard, the exposure of the crop and the possibility for a farmer to implement a coping strategy. To better understand the 'when', we identify three types of CMs based on the literature.

In section 2, a conceptual design is proposed to classify three types of CMs. In section 3.1, three streams of literature are reviewed to assess the extent to which they address CMs. The three types of CMs, and their dimensions related to hazard occurrence, vulnerability and coping, are further examined and classified in section 3.2. Section 4 discusses three key recommendations to apply the concept in practice.

2. Conceptual design

The CM concept integrates the time dimension of hazards, their effects on crop production and their impacts through different pathways on farm incomes. An initial conceptualization of critical moments was suggested by Groot et al. (2017). Here, a three-type conceptual design is developed to structure evidence on CMs. It considers direct and indirect impacts and provides insights into flexibility to cope with the hazards. The CM concept explicitly includes the total effects of individual and multiple hazards by crop stage covering the cost of coping. Based on this design we synthesize findings from the literature to answer the research question presented above.

The Immediate Impact CM (Fig. 1A) describes a CM arising from vulnerability to a single weather hazard, like a heavy rain after sowing causes waterlogging and results in seedling death or an un-seasonal rain between sowing and germination stage leads to crust formation and blocks seed germination. It causes loss of resources used for first sowing and farmers need additional resources for re-sowing as a coping option. Another example is a heat stress or waterlogging around the reproductive stage, which directly affects crop growth and leads to yield losses. In such situations, coping is hardly possible, either due to very short response time or due to no coping option for the pathway to loss; the crop never recovers to its full yield potential.

Compound Impact CM (Fig. 1B) represents a CM arising from the combined effect of two hazards, like a seasonal drought affecting crop development in the initial crop growth stage and a windstorm at maturity that produces lodging. Even if there is a coping possibility for a hazard at one stage, it has a cost and affects net income. The second hazard at a later crop stage with the fewer coping possibility (limited time to respond or no coping options) leads to higher yield loss. The compound effect of two or more moderate hazards can amplify vulnerability (IPCC, 2012). Yield loss and the costs of coping determine the net impact of a CM. Another example is the simultaneous occurrence of two hazards that have a synergistic effect, like moisture stress coupled with heat stress at the grain-filling stage.

The Shifted Impact CM (Fig. 1C), depicts the ripple effect of a hazard and an initial attempt to cope, like a weather event that causes a farmer to shift sowing or harvesting, which then affects the next crop under a double cropping system. The main impact is shifted to the next crop season with no or minor losses, during the first season. For example, an un-seasonal rain at maturity may delay harvesting of a first crop, leading to a conflict between harvesting and seedbed preparation operations, compelling farmers to delay or abandon sowing of the next crop, resulting in yield loss in the next crop.

We review climate modelling research to synthesize hazard frequencies for critical time periods relevant to crop production. Risk is defined as the product of the probability of a hazard and its adverse consequences (IPCC, 2012). For the causal relationship between a weather hazard and yields considering threshold levels for the different crop growth stages, we included CM-relevant examples from agronomy research. We review socio-economics research to link these effects to farm incomes. Where reported, examples on indirect impacts, including weeds, diseases, quality or workability issues were also included from these streams of literature.

The conceptual design informed the inclusion and exclusion criteria for the literature (Annex A). Based on these criteria, 721 papers and reports were collected. Out of these, only those that explicitly described time-related aspects of climate risk, with respect to the occurrence of a climate hazard, coping possibility and/or its impacts were further screened, reducing the number to 126. References to literature covering CM relevant issues such as workability issues, quality and cost of coping at specific moments expanded the total to 135. Our review aggregates prior findings on different aspects of hazards and their impacts. The review scope was confined mainly to syntheses of hazards during crop production due to weather variability, biophysical impacts of adverse weather events and other indirect pathways causing yield and income losses. The examples, by type of CM, consider crop vulnerability by crop stage and pathways to loss by type of hazard. For coping, possible coping options, and associated costs are considered. The concept of CM integrates these dimensions to assess the vulnerability of crop production based livelihood systems. The hazards we included are similar to the simple extremes referenced by the IPCC (2001) in its typology of climate extremes and described as individual local weather variables exceeding critical thresholds, like high or low temperatures, high or low rainfalls and extreme winds (Seneviratne et al., 2012).

3. Results

3.1. Elements of CM derived from literature

3.1.1. Climate modelling studies

Climate modelling science tends to focus on long-term changes in mean climate variables and their impacts like temperature extremes, seasonal droughts and increased stress due to excess water over land areas (IPCC, 2007; IPCC, 2018). Most research follows a top-down approach, both temporally and spatially, to study changes in extremes under different scenarios (Stocker et al., 2013), though some climate modelling does attempt to differentiate climate hazards at smaller temporal and spatial scales. Initial data and model limitations have made it difficult for climate modellers to converge on a certain crop growth stage during the year at a spatial scale sufficiently specific to identify CMs (Rosenzweig et al., 2014). Recently, though, climate modelling studies have converged down from the global to the regional scale (Stocker et al., 2013) and started to identify the most sensitive time windows over the crop growth cycle wherein variability in climate factors explain maximum variability in crop yields. For example, a spatial assessment of heat stress in wheat, maize, rice and soybean at the global level found a high risk of yield losses at the reproductive stage for many parts of Asia and central North America (Teixeira et al., 2013). Similarly, a study on winter crops in Australia identified the reproductive stage as the most sensitive to climate hazards, explaining up to 88% of yield variability (Shen et al., 2018).

This stream of literature has typically focused on heat stress and to a lesser extent drought, leaving other weather hazards over the crop production cycle under-illuminated. The analysis of the exposure of global harvested areas of rice, maize, soybean, and wheat found that exposure to five days above critical temperatures in the reproductive stage will likely increase globally, from 8% to 27% for rice, from 15% to 44% for maize and from 5% to 18% for wheat from 2000 to 2050 (Gourdji et al., 2013). Simulations of the impact of extreme heat and frost on wheat yields show that frost causes the greatest damage at the reproductive stage, while heat stress tends to affect the grain formation stage (Barlow et al., 2015). In contrast, the heat tolerance of cassava increases its suitability in large parts of Africa under future climate projections although the changing geographic distribution of pests and diseases is likely to bring additional challenges at different crop stages (Jarvis et al., 2012). Other vulnerability mechanisms from the climate modelling literature aligned with our CM concept include precipitation deficits (seasonal droughts) and excess soil moisture. Even small projected changes in the available period of cultivation due to changes in seasonal precipitation and flooding were found to affect the stability and productive capacity of the multiple rice crop system in Vietnam Mekong Delta (Kotera et al., 2014).

In general, climate science studies highlight the probabilities of unseasonal weather events and their implications on yield. The assessment of probabilities and magnitude of such anomalies can aid in making a timely adjustment and avoid losses (Rosenzweig et al., 2001). The projection of these anomalies is mostly on a large temporal and spatial scale. There is greater uncertainty about when, where and how much these predicted anomalies climate change will manifest (Heltberg et al., 2009). Explanations for crop vulnerability during the crop cycle to individual stresses during different crop stages over a production system scale are seldom explained in climate modelling literature.

3.1.2. Agronomy studies

Agronomy research typically uses experiments and modelling to discern cause and effect relationships between weather variables, and fluctuations therein, and crop yields. For most crops, upper and lower thresholds of these variables have been established for different phenological stages (Luo, 2011). Sensitivity at the different stages (time) to levels of stress (magnitude) relates strongly to the CM concept. The effect of different hazards varies with the growth stage of the individual crops concerned. For cereals, the reproductive stage is usually held to be more sensitive to drought and heat than the vegetative stage. Each stress influences the reproductive process differently (Barnabas et al., 2008), as pollen viability, fertilization and grain formation may be affected (Hatfield et al., 2011).

Similarly, to climate modelling studies, the most reported CMs are temperature-related. Temperature extremes, in the form of either heat stress or cold stress, damage crops differently at different stages (Bhandari et al., 2017). Temperature thresholds, critical months and thresholds for critical crop stages have been studied at the regional level, such as for rice crops in Asia (Wassmann et al., 2009a). The reproductive stage of rice is considered more sensitive to heat than the vegetative stage, with reduced grain weight in rice due to spikelet sterility (Wassmann et al., 2009b). Wheat yields are more affected by heat stress at the early grain-filling stage (Luo, 2011). Experimental studies have further differentiated crop sensitivities to time duration of exposure. Short exposure to high temperatures at anthesis drastically reduces spikelet fertility, which drops from 80% to 20% with a two-hour exposure to 38 °C, and falls to zero if a rice crop is exposed to 41 °C for more than one hour (Yoshida, 1981). Rainfall variability is another hazard often reported for different CMs. Both heavy rainfall and drought at different stages affect germination, weed infestation and insect and disease incidence (Chakraborty and Newton, 2011; Juroszek and von Tiedemann, 2013). Other vulnerability mechanisms aligned with our CM concept are seasonal droughts or excess soil moisture due to heavy rain at different stages in a variety of different crops and regions (Groot et al., 2018; Siderius et al., 2016b; Van Oort et al., 2012; Wassmann et al., 2009a). The accumulated impacts of a combination of abiotic stresses like heat and moisture stress are also studied (Hussain et al., 2019; Zandalinas et al., 2018). Rains with storms can be particularly damaging and mostly cause lodging that leads to heavy losses for example 60–70% diminishment of yield in wheat (Berry and Spink, 2012). Agronomy research helps to understand the pathway to loss and quantify the effect of weather stresses on yield by crop stage and tends to be more detailed in its definition of crop vulnerability, but generally does not consider hazard frequency, the effectiveness, and costs of coping and associated vulnerability at crop production system level.

3.1.3. Socio-economics studies

The social sciences provide qualitative and quantitative measures to describe risk and risk causation processes (Cutter, 2010; IPCC, 2012). This discipline employs costing and valuation methods to measure the impacts of uncertainties (IPCC, 2001; Prettenthaler et al., 2016), and econometric models that integrate long-term weather and crop production variables as well as household survey data to draw conclusions on climate risk management and the impacts of climate hazards on yield stability, farm income, food security and farmers' coping strategies (Ben-Ari and Makowski, 2016; Ma and Maystadt, 2017; Molua, 2011). Many studies explain seasonal level yield variability at large spatial scale employing statistical techniques using time series meteorological and crop yield data (Ray et al., 2015), and correlate these with crop stages (Hlavinka et al., 2009). Hazards related to CMs that are reported in the social science literature tend to be more varied, from heavy rains during planting or harvesting periods, long early season droughts, to warm winters and unusual weather events like hailstorms (Diogo et al., 2017).

Table 1
Summary of different types of CMs from the examined literature.

Type of CM	Hazard	Time period/crop stage & pathways	Coping practice
Immediate Impact CM	Dry/wet season	Sowing: Workability, cost, short season, loss of seed vigour	Late sowing, Potato, Netherlands (Schaap et al., 2011); NA, Potato, (Van Oort et al., 2012)
	Low temperature	Germination: Seedling death due to frost or advanced senescence	NA ('Not Applicable' for reported CM for which no coping is specified), Wheat (Barlow et al., 2015); Delayed planting, wheat, Australia (Fuller et al., 2007)
	Low temperature T. extremes	Germination: Root damage	Early sowing, Wheat, Netherlands (Schaap et al., 2011; Schaap et al., 2013)
		Germination: Seedling death	NA, Wheat (Barlow et al., 2015); Food legumes, (Bhandari et al., 2017), NA, Food legumes, (Bhandari et al., 2017); Wheat, (Porter and Gawith, 1999)
		Vegetative: Leaf damage, soil-borne diseases	NA, Wheat (Barlow et al., 2015); Food legumes, (Bhandari et al., 2017)
		Vegetative: Stunted growth, diseases	NA, Food legumes, (Bhandari et al., 2017); Wheat, (Porter and Gawith, 1999)
	Wind, rain	Vegetative to maturity: Lodging, more time and cost to harvest, quality issue	Planting method, date of sowing (DoS), Plant population, nutrient & disease management, Cereals, (Rajkumara, 2008); Seeding rate (SR), adjust DoS, tillage & fertilizer, Cereals, (Shah et al., 2017); Rice, Japan (Ishimaru et al., 2008)
	High temperature, Heat stress, T. extremes	Reproductive: Yield and quality loss	Change of variety (CoV), Soybean, USA (Salem et al., 2007); NA, Wheat, (Nuttall et al., 2017)
		Maturity/ Ripening (lodging, yield & quality loss)	NA, Canola, Canada, (Wu and Ma, 2018); NA, Canola, Canada, (Wu and Ma, 2018)
		Reproductive: low yield	CoV, DoS; Wheat, maize, rice and soybean, Asia and Central North America (Teixeira et al., 2013); Maize and rice, (Gourdji et al., 2013); irrigation during flowering; Rice & Wheat in Pakistan (Arshad et al., 2018); (Arshad et al., 2017); NA, Rainfed maize, USA (Lobell et al., 2013)
		Reproductive and grain formation: small grains, affect the composition of protein and starch (quality), higher probability, forced maturity	CoV; Wheat, (Luo, 2011); Indus delta (Rasul et al., 2012); NA, Maize, Argentina (Mayer et al., 2016) Changing DoS, Wheat, China (Liu et al., 2014a); Heat tolerant variety (HTV), shifting DoS, seasonal weather forecasts, direct drill seeding; Rice, S. Asia, (Wassmann et al., 2009a); HTV (Stratonovitch and Semenov, 2015)
		Reproductive (grain filling): higher probability & variability, sterility, grain shrivelling, affect quantity and quality, pest and diseases, yield and quality	CoV, change DoS, IPM; Maize, sorghum, cotton, rice, bean, soybean and wheat, (Hatfield et al., 2011); weather forecast, intercropping, shift and adjust management practices, IPM; Wheat, rice, maize, (Tripathi et al., 2016); NA, Legumes, maize, rice, (Luo, 2011); Cereals, (Hatfield et al., 2011); Wheat, (Porter and Gawith, 1999); Wheat, rice, maize, (Tripathi et al., 2016); Crops, USA (Wienhold et al., 2018); Food legumes, (Bhandari et al., 2017); Rice, Philippines (Shi et al., 2017); Wheat, (Barlow et al., 2015); Wheat, (Porter and Gawith, 1999); Winter crops, Australia (Shen et al., 2018)
	Heavy rains	Vegetative: Submergence	Drainage, rainfed rice, Bangladesh, (Wassmann et al., 2009a)
	Less rain (Dry spell)	Vegetative: Poor crop establishment	Supplement irrigation, Onion, Netherlands (Schaap et al., 2011; Schaap et al., 2013): Partial irrigation, and shift DoS, drought tolerant variety (DTV), soil and water saving tillage, crops, Czech Republic (Hlavinka et al., 2009); DTV Aman rice; Rainfed rice in Bangladesh, (Wassmann et al., 2009a); nutrient and pest management, maize and soybean, USA (Teasdale and Cavigelli, 2017)
		Reproductive & Grain filling: higher dry spell probabilities, most sensitive stage, reduction in the rate of net photosynthesis, and poor grain set and grain development	Improved field water management strategies, water harvesting, Maize, Africa (Barron et al., 2003); HEIS, Maize, (Tripathi et al., 2016); DoS, conservation agriculture, Grain legumes, Tropics (Farooq et al., 2017); DoS, DTV and fertilizer inputs, wheat, Global (Asseng et al., 2015)
	Unseasonal rain (heavy rains) Hailstorm	Maturity/harvesting: Anaerobic condition rotting, Pre-harvest sprouting, quality, and value, wet fields, workability, cost, delay harvest, soil compaction, rotting of tubers, no harvest	Drainage, Potato, Early planting and harvesting, Netherlands (Schaap et al., 2011; Schaap et al., 2013); NA, White wheat Australia, South Africa, Canada, Central Asia and Europe (Biddulph et al., 2008); Weather forecast, Sugarcane, Swaziland (Mhlanga-Ndlovu and Nhamo, 2017)
		Maturity/harvesting, pest and disease,	

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Table 1 (*continued*)

Type of CM	Hazard	Time period/crop stage & pathways	Coping practice
			Early harvesting of maize and peanut, Senegal (Roudier et al., 2014).
		Different stages: Stand reduction and defoliation	Replanting at early growing season, row spacing, Maize, USA (Battaglia et al., 2019; Vorst, 1991);
Compound Impact CM	High temperature at early crop stages	Sowing and germination: delay sowing, poor growth, reduced tillering, dry weight, exposure to stress at later stages	Change date of sowing (DoS), Wheat, (Porter and Gawith, 1999); Wheat S. Asia, (Wassmann et al., 2009a); (Sivakumar and Stefanski, 2011); DoS, cold storage for seed, Potato, Netherlands (Schaap et al., 2011; Schaap et al., 2013); Supplement irrigation, Rice, (Shah et al., 2011); HTV, Rice, Asia, (Wassmann et al., 2009b)
	Unseasonal rain (Wet or dry)	Sowing/transplanting; higher probability of exposure to extreme events later in the season	DoS; Potato, the Netherlands (Van Oort et al., 2012); adjust DoS with rain, Rice, North-east Thailand (Sawano et al., 2008); delayed transplanting; Rice, Indonesia- (Rosenzweig et al., 2001)
	Moisture & frost	Germination: delay sowing, poor crop establishment (frost)	Early sowing with supplemental irrigation; Wheat, Turkey, (Ilbeyi et al., 2006)
	Humidity & high night temperature	Reproductive: sterility	HTV, DoS, and exogenous application of plant hormones, Rice-review (Shah et al., 2011)
	Low rain and frost Moisture and heat stress High humidity (rain), wind	Reproductive & grain filling; sterility, low yield, Pest outbreak, high cost, Synergistic effect on the photosynthetic process of both high and low temperature under moisture stress, exacerbate the adverse effect of high temperature, The combined effects of high temperature and drought were greater than additive effects for leaf chlorophyll content, grain numbers and harvest index in wheat	Cross stress tolerant varieties, wheat, USA (Shah and Paulsen, 2003); NA wheat USA (Prasad et al., 2011); wheat and maize, (Suzuki et al., 2014); NA Barley Germany (Rollins et al., 2013), Lentil, India, (Sehgal et al., 2017); Wheat, Germany (Mahrookashani et al., 2017); Insecticide; Soybean, USA (Rosenzweig et al., 2001); reduced tillage, mulching & weed control; Corn & soybean, USA (Teasdale and Cavigelli, 2017); no specific coping recommended (NA), Maize, USA (Hatfield et al., 2018); Cereals, (Wang and Frei, 2011); Maize, USA (Westcott et al., 2005); Cereals, (Barnabas et al., 2008); Perennial grass, China, Improvement in thermotolerance by genetic methods (Xu and Zhou, 2006).
	Moisture extreme & frost/heat/wind	Reproductive: Pollen viability	NA, Rice, (Tripathi et al., 2016); Japan, (Matsui et al., 2005)
		Reproductive: Lodging	NA, Cereals, (Berry et al., 2004); NA,, Wheat, UK (Berry et al., 1998)
	High temperature and humidity heavy rain (wet)	Reproductive: Spikelet sterility	Adjustment of DoS, choice of varieties, and exogenous application of plant hormones; Rice, (Wassmann et al., 2009b); (Shah et al., 2011); NA, rice China (Yan et al., 2010)
		Early crop stages and later (reproductive to maturity) stages yield loss	NA, wheat, France unprecedented yield loss (Pfleiderer et al., 2021)
		Maturity: Fungi infection	Chemical protection, Seed onion, Netherlands (Schaap et al., 2011; Schaap et al., 2013);
	Wind & rain	Different stages: Disease, lodging, management issues, pests and pathogen, mycotoxin with rains, quality issues,	Early ripening cultivar; wheat, Europe (Trnka et al., 2014); pesticide; Brazil, Uruguay, Argentina and the UK; Crops, (Chakraborty and Newton, 2011); NA; Arable crops, Europe, (Trnka et al., 2015)
	Multiple stresses (different stages)	Different stages: Decrease in gross margins & total NPV	NA, Seed onion, potato, wheat and sugar beet, Netherlands (Mandryk et al., 2017); Arable farming, Netherlands (Diogo et al., 2017)
	Unseasonal rain & storm	Harvesting (rice), Sowing/grain formation (wheat): wet field, lodging, workability heat stress	Adjusting DoS, weather forecast, crop insurance, No till for early wheat sowing, Short duration rice varieties; Rice-Wheat system, S. Asia, (Wassmann et al., 2009a); (Arshad et al., 2017)
	Unseasonal rain & storm & high temperature	Early stages: affecting the cropped area & cropping intensity	NA, Crops, (Iizumi and Ramankutty, 2015); Seasonal forecast, Philippine (Koide et al., 2013), NA Rice, Vietnam (Kotera et al., 2014)
		Grain formation & harvesting: Tuber bulking stage. Heat stress in both rice and wheat in rice wheat system	Supplement irrigation on well-drained soil, Potato, US (Woli and Hoogenboom, 2018); Short cycle cultivars, early rice harvesting and wheat sowing varieties (Arshad et al., 2018)
Shifted impact	Heavy rain	Harvesting, Wet field, workability issue for harvesting & land preparation, higher cost, quality loss, delay sowing of next crop, heat stress in wheat	NA, Wheat, Netherlands (Schaap et al., 2011); Early sowing & harvesting, Potato, Netherlands (Van Oort et al., 2012); Drainage (rice filed), early wheat sowing by surface seeding with weed control (Krupnik et al., 2015)
	Unseasonal rain	Sowing and harvesting: workability issues and delay in sowing and harvesting operations, which narrows the time for maturity and harvesting	Adjusting sowing and harvesting dates, preparation of planting beds, Potato Netherlands, (Schaap et al., 2011; Schaap et al., 2013): Weather forecast, Sugarcane, Swaziland (Mhlanga-Ndlovu and Nhamo, 2017); Early

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Table 1 (*continued*)

Type of CM	Hazard	Time period/crop stage & pathways	Coping practice
			sowing with ZT drill, rapid rice harvesting, Rice & Wheat in Pakistan (Arshad et al., 2018); NA, rice Philippine (Sawano et al., 2008)

NA = Not applicable where no coping is specified; DoS = Date of sowing; DTV = Drought tolerant variety, HEIS = High efficiency irrigation system; HTV = Heat tolerant variety; SR = Seed rate; CoV = Change of variety.

Examples from the socio-economics literature, though fewer, tend to link hazards to more aggregated outcomes like household income. The crop revenues were found to be harmed by extreme heat exposure and the cropped area also declined where an increase in extreme heat was more severe (Burke and Emerick, 2016). The estimates of the impacts do vary when the impact with adaptation is included (Butler and Huybers, 2013). Farmers reduce aggregate input quantity in response to detrimental weather conditions. Weather conditions at different crop stages do not only have a direct effect on production, but also indirectly via reductions in inputs which are not often captured in economic models (Ortiz-Bobea et al., 2021). Farmers growing maize in US cope by reducing aggregate input quantity in response to detrimental weather conditions (Butler and Huybers, 2013). Farmers' knowledge about variability and changes in climate and the perceived risks of extreme events determines their willingness and ability to adapt crop production systems (Abid et al., 2019). Local knowledge about climate hazards and farmers' coping practices is considered a source of relevant adaptation practices (Ogalleh et al., 2013). However, despite the considerable socio-economic literature on farmers' perceived risks of extreme events, focus is largely on ex-ante coping practices, such as planting decisions, or ex-post coping strategies, e.g., in terms of alternate livelihood options, and less on those decision taken during the cropping season (Shah et al., 2020).

In terms of specific critical moments, distinct intra-seasonal fluctuations of temperature and soil moisture were identified, with specific emphasis on the risks of extreme cold after planting and high temperatures at maturity in winter varieties of wheat and barley (Gammans et al., 2017; Tack et al., 2017). Different environmental stressors were found having time-varying effects during different crop stages to crop yields (Ortiz-Bobea et al., 2019; Urban et al., 2012) though most seasonal level effects are still difficult to link to stresses at specific period of crop growth as the time series does not include historical adaptations (Schlenker and Roberts, 2009). Recent studies have investigated the impacts of future climate, biophysical and socio-economic conditions using integrated assessments and scenario analysis from the local to the national level identifying detailed crop-specific CMs (Antle et al., 2015; Roberts et al., 2017; Schaap et al., 2011; Schaap et al., 2013; van Wijk et al., 2014) with some putting specific emphasis on shifts of growth phases over time (Dalhaus et al., 2018). But generally, little evidence is reported related to specific CMs and associated agronomic costs of coping and the net impact on agricultural livelihoods.

With socio-economic research primarily relating hazards and vulnerability to yield loss, other associated pathways including workability issues, quality concerns, additional cost involved for coping with such hazards during the crop season that contribute to vulnerability, tend to be underreported, the development of weather index based flexible insurance designs, studying the impact of weather hazards during the crop growing period (Conradt et al., 2015; Tack et al., 2018), being an exception. With increase in the frequency and severity of weather extremes, the costs for adaptation measures were found to strongly reduce gross margins under future scenarios (Mandryk et al., 2017). With increased risks due to climate change and higher losses expected, the cost of insurance is projected to increase (Perry et al., 2020; Tack et al., 2018). The nature of the methods applied – econometric models – would allow for analysis of such associated pathways without the need for full process knowledge or the explicit inclusion of all hazards in process models. It should also be relatively straightforward to assess compound effects through econometric methods.

3.2. Integrating hazard occurrence, crop vulnerability and coping; three types of CMs

To derive a time-specific description of the risk and classify different CM we integrated the hazard risk aspect from climate literature and the crop vulnerability findings from agronomic literature with coping strategies as described mostly in socio-economic literature. Considering the direct and indirect impacts of climate hazard and coping possibility during the crop production cycle, three types of CMs are classified, here presented in order of complexity.

3.2.1. CM's with immediate impact

If a hazard has a direct impact on crop development or required coping strategies have a strong impact on income we define them as Immediate Impact CMs (iCMs). A thick surface crust formed following rain after wheat sowing, can lead to very low or no germination and require re-sowing. In such a case, farmers must bear the extra cost of immediate re-sowing at a time when the availability of seeds is often limited and labor scarce, which drives up costs (Shah et al., 2020). A simplified example of such an iCM is presented in Fig. 1A. I- CMs can also occur at other crop stages.

Most commonly reported in the literature are temperature related iCMs with increased risk especially at later crop stages (see Table 1 for an overview). High yield losses occur at the reproductive stage in summer legumes (Bhandari et al., 2017), soybean (Salem et al., 2007), wheat (Liu et al., 2014a), maize and soybean (Hatfield et al., 2018; Teasdale and Cavigelli, 2017) and rice (Shah et al., 2011). Heat stress at the grain filling stage of wheat also causes losses, with sudden exposure to higher temperatures more devastating than gradual exposure to heat (Luo, 2011). Losses from such iCMs are inevitable as there is hardly a coping option available after the crop is exposed to heat stress. The second most reported iCMs relate to moisture stress or excess, occurring at different crop stages for different crops. In sorghum in sub-Saharan Africa, germination is often affected, while also during the tillering stage a crop is vulnerable (Hadebe et al., 2017). In the northern Netherlands, dry weather between March and April leads to late or no sowing of seed potato (Schaap et al., 2011). In maize in semi-arid eastern Africa, moisture stress was found to cause up to a 75% yield loss at the flowering stage and 40% at the grain-filling stage (Barron et al., 2003). Moisture related CMs are more common in rainfed agriculture, as farmers have limited or no coping options and severe yield losses or even crop failure is a likely outcome. Other CMs of the immediate impact type often mentioned, relate to crop lodging due to a windstorm at the maturity stage, e.g. in wheat (Berry and Spink, 2012; Shah et al., 2017).

A hazard affects more than just the volumetric yield of a crop; often it also affects yield quality, which can render a crop unmarketable. An iCM may indicate the period of a heightened risk of such a loss of quality of the produce. For example, temperature variability at different crop stages affects not only yield quantity but also quality (Tripathi et al., 2016), as both photosynthesis and enzyme activity are affected (Porter and Gawith, 1999). High daytime and night-time temperatures during the grain-filling stage diminish the quality of rice (Shi et al., 2017). A study of heat stress at the late kernel growth stage in four maize genotypes found that both protein and starch content decreased up to 38% (Mayer et al., 2016). Other examples are potato tubers rotting due to heavy rains (when producing anaerobic conditions for 24 h or more) and mycotoxins forming in winter wheat due to humid weather at maturity (Schaap et al., 2011).

We define a critical moment not only by a crop's vulnerability at different crop stages. CMs also arise by the lack of affordability or inability to timely respond (due to labor or some other constraint) to avoid yield loss. Along with biophysical impacts, weather hazards disrupt farm management and field workability, causing conflicts in the timing of crucial farm operations and labor allocation. Additional costs incurred due to workability issues often arise from too wet conditions at sowing (Kistner et al., 2018) and constraint the use of heavy machinery during harvesting (Cooper et al., 1997). The literature provides examples of a number of workability issues such as overly wet or cool weather causing lodging and difficulty in wheat and potato crop management in Europe (Schaap et al., 2011; Trnka et al., 2014; Van Oort et al., 2012), wet conditions constraining the use of heavy machinery in Scotland (Cooper et al., 1997) and management, labor and machinery conflicts during maize planting in the central USA (Kucharik, 2006). Similarly, crop lodging due to wind or a storm can cause workability issues, making harvesting operations then more difficult, and taking more time, against increasing cost (Berry et al., 2004).

A good example of a stock-taking of associated economic impacts of seasonal climate risks is that done for the arable regions of the Netherlands (Schaap et al., 2011; Schaap et al., 2013). Based on economic impacts, major risks – those causing more than €1,000 per hectare losses annually – were heat waves causing secondary growth, warm winter temperatures inducing early sprouting of seed and ware potatoes, and higher temperatures and wet conditions contributing to fungal disease in seed onions. Greater climate variability and unstable weather reduce pesticide efficacy, leading to higher losses (Patterson et al., 1999). Evidence shows that regionally, too, particular weather conditions can induce disease epidemics and pest outbreaks on a large scale (Rosenzweig et al., 2001). These indirect impacts are difficult to measure, and the associated losses are hardly reported in the literature. The level of loss and coping possibility varies by the time of hazard incidence within the crop production cycle. In the US, the overall impact of hailstorms was found to be lower early in the growing season, even when damage is severe because of the option to replant; hailstorms later, between June and September, can cause losses of $52 million annually (Vorst, 1991). A review on hail influence on maize reported a progressive increase in yield loss from early vegetative to the reproductive stage (Battaglia et al., 2019). Most iCMs present a very small time window for adjustments and adaptations and farmers must be capable to invest additional resources (often incurring a higher cost) to prevent yield losses. On the other hand, at early crop stages, farmers foresee the impact, which provide them a larger time window to ameliorate the outcome and give some flexibility to decide between on-farm and off-farm coping options, like temporary work in cities.

Beside yield, weather influences cropping area intensity (Iizumi and Ramankutty, 2015) like a delayed monsoon in Thailand limits water for seedbed preparation which reduces the area planted with rice (Sawano et al., 2008). There is a higher financial impact on farm income if decrease in cropped area is accounted along with other direct and indirect impacts. When a single hazard affects crops via multiple impact pathways this often leads to higher yield and income loss. A dry spell during the reproductive stage of groundnut crop, grown under rainfed conditions in the Pothwar region of Pakistan, causes loss through insect attack (additional cost of insecticide) as well as yield loss due to reduced pegging. Similarly, rice farmers in irrigated plains of Punjab, Pakistan experience losses by insects as well as reduced grain setting due to higher pollen sterility from an exposure to high temperatures at reproductive and grain formation stages (Shah et al., 2020).

3.2.2. CM's with compound impact

Occurrence of two or more hazards, even if moderate, over a single crop cycle increases vulnerability (IPCC, 2012). Compound CMs (cCMs) impacts arise either when one - potentially moderate - hazard is followed by another later in the cropping season (as depicted in in Fig. 1B) or when the effect of one hazard at a sensitive crop stage is exacerbated due to the simultaneous interaction with another stress condition. Impacts are exacerbated when the farmer has less capacity to cope with the second hazard- e.g. having spent all finances to coping with the first - or if there is no coping strategy at later crop stages. Several studies have started to examine the probability of multiple hazards within a season. Data from 14 sites representing wheat-producing regions in Europe suggest that the likelihood of two hazards per season doubled under one projected scenario, and rose more than six-fold under the most severe global climate model compared to the baseline and were likely to affect 11 of the 14 sites (Trnka et al., 2014). Another analysis for 379 European sites indicated that every site was prone to the risk of multiple hazards during the wheat production cycle (Hlavinka et al., 2009; Trnka et al., 2015). In other regions, increasing probability and intensity of temperature and rainfall extremes have recently been reported as well (Naveendrakumar et al., 2019; Sun et al., 2019; Umar et al., 2019; Xu et al., 2019).

Sequential cCMs originate when a hazard at an early crop stage with lower coping capacity, increases a crop's vulnerability or increases a crop's exposure to a second hazard later in the season. Moisture stress at the sowing stage under rainfed conditions causes delay in wheat sowing and exposes the crop to higher risk of heat stress later in the season. Similarly, a decrease in temperature at sowing stage causes slow germination or may require re-sowing of the wheat crop in high mountains of Pakistan. This delay may expose the wheat crop to higher risks of low temperature later in the season when an early onset of winter can jeopardize a good yield (Shah et al., 2020). Other examples of sequential cCMs were reported from Belgium, for winter wheat, barley, potato, sugar beet, maize, and rapeseed. High rainfall with low radiation in spring, moisture and heat stress at grain formation followed by storms at maturity resulted in low wheat yield. Frost in the early season, dry spell in the mid-season and high temperature during the late season resulted in low winter barley yield. Similarly, low maize yields and low winter rapeseed were associated with the combined impact of multiple hazards at different crop stages (Gobin, 2018). An unprecedented wheat crop loss in northern France during 2016 is attributed to a combination of a warm winter followed by wet conditions during spring (Pfleiderer et al., 2021).

Weather hazards occurring simultaneously often create complex CMs due to the extra demand for labour or inputs. Examples are soil moisture stress that exacerbates the effect of heat stress at the reproductive stage (Hatfield et al., 2011) and high humidity alongside high daytime temperatures during the reproductive stage of rice plays a role in increasing spikelet sterility (Shah et al., 2011; Wassmann et al., 2009a). Wheat producing regions across the world are likely to have concurrent heat and moisture stress leading to high yield losses (Mahrookashani et al., 2017; Mukherjee et al., 2019; Qaseem et al., 2019; Toreti et al., 2019), and the compound effect was found to be higher than the additive effect of individual hazards (Prasad et al., 2011). Both high and low temperature under moisture stress produces a synergistic effect on the photosynthetic process in wheat in the USA (Prasad et al., 2011). Our review found that high temperatures and drought are the hazards most commonly reported as simultaneously affecting crop growth and yield especially at the reproductive stage. A cCM exists either because the crop is more susceptible (e.g. less well-developed roots) or because coping capacity is reduced (e.g. finances have been exhausted to cope with earlier hazards). In the high mountains of the Hindu Kush Himalayas, low temperatures followed by a frost spell after the wheat crop is planted causes seedling death at germination and it reduces water supply due to low snow melt while the crop at this stage requires irrigation not only for growth but also as a coping strategy to reduce losses from wilting of the crop under low temperature (Shah et al., 2020).

The impact is exacerbated as the same hazard limits coping possibility and increases the risk of a second hazard. Multiple hazards can produce conditions conducive for pest and diseases, like high temperature and high humidity near onion maturity causing fungal infection affecting quality and requiring additional costs for chemical protection (Schaap et al., 2011; Schaap et al., 2013). Moisture and heat stress at the grain formation stage also affect the quality and reduces feed value of maize, wheat and barley (Wang and Frei, 2011). A windstorm with heavy rain causes higher crop lodging at later crop stages and higher yield loss along with workability issues (Berry et al., 2004). Under field conditions the crops responses become complex if multiple stresses occur simultaneously (Suzuki et al., 2014). Multiple hazards can lead to higher income loss. cCMs were found to have a significantly higher impact than the individual CMs (Zandalinas et al., 2018).

3.2.3. CM's with shifted impact

In regions dominated by integrated multi-cropping systems – i.e. most of the world breadbaskets - the complexity further increases when CMs are defined across crop seasons. A weather hazard during one crop season might have no serious consequences, but it may nonetheless affect yield or lead to conflicts in terms of the allocation of land, finances or labor in producing the following crop, thereby cascading impacts and raising costs. This we classify as a 'shifted impact CM' (sCMs). In most double-crop systems, such sCMs are important (see Fig. 1C).

Cascading impacts originate from conflicts in the allocation of land, labor, machinery and other resources in different multi-crop systems. The most reported sCM of this kind is the harvesting season of the first crop, when un-seasonal rains may delay harvesting, pushing back the sowing of the next. This reduces the period available for the necessary farm operations and disrupts the next crop's production cycle, as in multi-crop rice systems in the Mekong Delta (Kotera et al., 2014) and South Asia's rice–wheat cropping systems (Arshad et al., 2017; Shah et al., 2020). On the irrigated plains of Punjab, a minor weather hazard like a wind at rice maturity stage or even just modest rain event at rice harvesting makes harvesting and threshing operation difficult causing higher cost as well as delay in wheat sowing, causing an estimated 8–18% yield loss in the following wheat crop (Shah et al., 2020). Other studies of the rice–wheat growing region of South Asia found that in Indian Punjab, a delay in rice harvesting due to weather or management issues and resultant late sowing of wheat led to yield losses of 0.7–0.8% per day of the delay after 15 November (Ortiz-Monasterio et al., 1994) or an average decrease the potential wheat yield by up to one ton per hectare (Aggarwal et al., 2000). In the wheat-maize system in the northern mountains of Pakistan, rainfall and/or low temperatures cause a delay in wheat maturity resulting in a delay in wheat harvesting (Shah et al., 2020). This pushes maize sowing back with an early onset of the winter season affecting its grain formation so that farmers can only use it as fodder.

A focus on CMs can reveal more tentative links between the moment of the initial hazard and the final impact: In the rice–wheat cropping system of Pakistan, Shah et al. (2020) found that a '*Jhakar*' (storm) immediately after the rice transplanting, before the seedling is fully rooted, often results in complete or partial uprooting. As a coping option, framers need to arrange labour and replacement seedlings immediately to fill the gaps, but often there are delays with many agricultural activities competing for labour and the widespread nature of the event leading to a lack of seedlings in nurseries nearby. Even if full re-transplanting can be avoided, the use of seedlings of different age or variety results in differential ripening which affects the quality at harvesting and often pushes the harvesting date backwards, thereby affecting the time available to plant the subsequent wheat crop. This again increases risk of heat exposure later in the season.

Summarizing across the literature evaluated, we found the reproductive stage most often reported as high risk, especially for iCM, with heat and moisture stresses the major hazards and wheat the most studied crop (see also Table 1). CMs during early growth stages are also relatively often reported, especially among cCM and sCMs, with a variety of coping options still feasible at this stage. In terms of complexity, most CMs studied were of the immediate impact type, followed by the compound type. The geographic spread indicates the more complex CMs with shifted impacts are only reported in few, often related studies from Europe and to a lesser extent mentioned in studies focussing on South and East Asia (Fig. 2). We found few CMs examples from South America and Africa in the literature. We also found few specific studies on the Middle East and Central Asia region, but because wheat is one of the major crops here, and with many global modelling studies focussing on wheat, the region is partly covered by the global count. The global count, with global coverage of climate variability hazards includes mainly studies on wheat crop.

4. Discussion and conclusions

Three types of critical moments, periods of heightened risk during the year when farm households are vulnerable to specific climate hazards, were defined and illustrated by examples from three streams of literature. Existing literature tends to focus on individual hazards or vulnerabilities; reported risk is high at early crop stages, when access additional resources to cope with hazards is often limited, and during the reproductive stage with many studies focussing on heat stress in wheat. Relatively little evidence exists on CMs due to compound or shifted impacts, despite the fact that an increasing number of people rely on crops grown in regions with high cropping intensities (Iizumi and Ramankutty, 2015; Liu et al., 2014b; Siderius et al., 2016a; Siebert et al., 2010), often in climate change hotspots (De Souza et al., 2015).

Differentiation of CMs can help to distinguish suitable coping mechanisms to ameliorate in-season losses, or to improve the livelihoods of vulnerable households by alternative means if in-season coping fails. As a framework, the concept of CMs is closely aligned with IPCCs definition of risk as a function of hazard, vulnerability and exposure (IPCC, 2012). While this definition is well known, our literature reviews shows scientific application tends to skew to one dimension depending on the research domain, with climate modelling focussing mostly on hazards, agronomy research on crop vulnerability and socio-economic research, sometimes including coping aspects.

To apply the CM concept, we consider three key recommendations: First, our findings point to the importance of integrating different disciplines to look at the vulnerability of agriculture in a holistic manner. General recommendations like 'adjust sowing time' or 'use short-season varieties' or 'shift to some other crop', made at the crop level and based on changes in mean temperature and/or precipitation, ignore in-season variability and overlook the limited flexibility farmers have once the crop is planted or even planned. Resource constraints in developing countries are often aggravated by the short time window to respond (Shah et al., 2020). Impact assessments should include coping complexities with respect to time limits and associated additional costs.

Second, take into account compound risks as climate change increases the likelihood of hazards occurring during the same crop season, if not at the same time (IPCC, 2021). The increase in frequency of extreme events, projected ten years ago by the IPCC (2012) is already being felt by farmers, especially those that farm at the margin (Hussain et al., 2019; Qaseem et al., 2019). To facilitate awareness and a better recognition of CMs, surveys design could be improved such that questions explicitly address the combination of crop vulnerability – hazard – coping strategies and their timing. Inclusion of all possible combinations could lead to a multitude of reported CM for any given cropping system. Often, however, farmers are well able to identify those CMs most relevant to them. In a study of 273 farm households for four cropping systems in Pakistan (Shah et al., 2020), farmers identified 61 CMs at different crop stages, from pre-sowing to harvesting, but classified six as most problematic due to the compound and shifted impacts. Given the

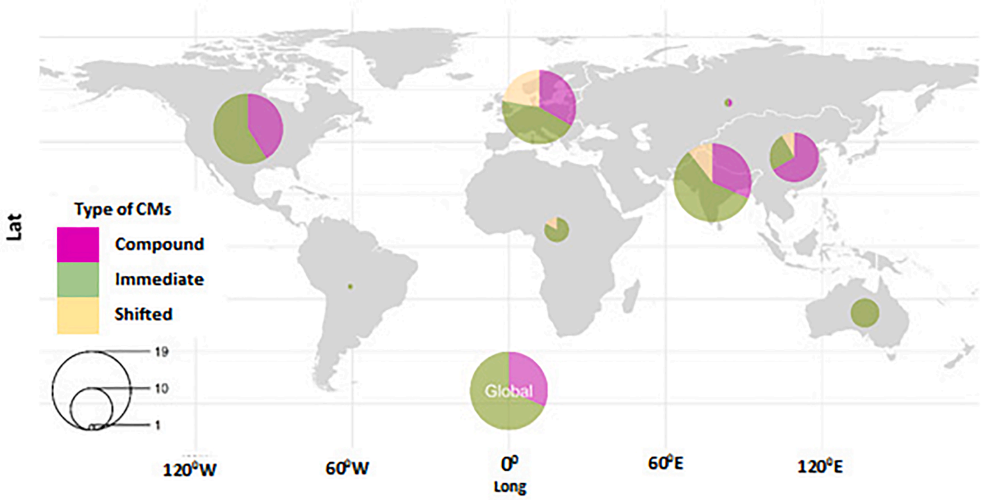

Fig. 2. Geographic distribution of the sample literature by type of CM. 'Global' CMs refer to global studies that report mostly on a crop level.

importance of food production, a consorted effort to identify the most relevant CMs, for dominant cropping systems in the most important food producing regions is warranted and would improve initiatives such as the Agricultural Model Inter-comparison and Improvement Project (Antle et al., 2015).

Third, assess the intensity of the cropping system and the duration between crops in rotation to appreciate the likelihood of cascading effects. Land and operational conflicts between crops in double-cropping systems that may arise under increasing climate variability need to be identified. The shifted impact CM also helps to characterize impacts in a connected system. Shah et al. (2021), show detailed conflicts in land and labour allocation, leading to workability issues affecting both crops in double cropping systems for various cropping systems. These cascading effects can extend beyond agriculture. For instance to the severe deterioration of air quality in South Asia, attributed in part to stubble burning farmers, has been linked to energy saving regulation at the start of the rice crop season, prohibiting farmers to use ground water before the monsoon. This forces farmers to delay the transplanting of rice and shortens the time available to prepare the land for the consecutive wheat crop (Mukherji, 2019). In order to anticipate and assess these risks, hydrology-crop and land surface models, meanwhile, should be improved to simulate multi-cropping (Biemans and Siderius, 2019; Mathison et al., 2021).

More practically, the CM perspective could contribute to user-relevant climate risk metrics and climate services such as the development of vulnerability maps integrating weather forecasts with crop stage sensitivities and coping options. Climate services can provide farmers timely information on changing planting times that will not coincide with periods of risk (heavy rains, heat waves etc) at a sensitive crop stage and extension services can train farmers in best risk management practices keeping in view the possibility and potential of coping options considering pathways to loss by type of hazard and array of losses. The analysis of CM can also support the insurance services in improving flexible weather-based index insurance design by capturing the hazards occurrence dates along the progress and shift of critical plant growth phases over time and space. Considering losses by hazards pathways could further reduce farmers' downside risk exposure (Conradt et al., 2015; Dalhaus et al., 2018).

Climate change will exacerbate existing risks, cascading potentially across multiple cropping systems, sectors and even regions *(*IPCC, 2019*)*. Extreme events may offset any positive impacts of mean climate change on farm economic performance and are expected to substantially undermine the future economic viability of crop farming (Diogo et al., 2017), with crop profitability varying significantly by climate hazard (Molua, 2011) and farmers' capacity to adapt to ameliorate yield loss (Moore and Lobell, 2014). A better understanding of climate risks through CMs can support the development of robust national and regional agricultural policies. To scale up from the farm level to the crop production system level, CMs could be integrated with scenario analysis and vulnerability threshold approaches (Diogo et al., 2017; Kwadijk et al., 2010; Wilby and Dessai, 2010). The diversity of climate risks needs an array of coping responses which are interdisciplinary in nature. The analysis of CMs can help target policy interventions and contribute to a diagnostic and planning framework to determine institutional fit for coping and adaptation responses and to complement climate services for the rural farm sector (Cuevas et al., 2021).

We argue that the identification of CMs under future projections would provide useful insights to inform risk management decisions and promote successful adaptation for sustainable crop production. Strategies proposed to deal with shifting and changing hazards range from reducing crop vulnerability through genetic improvement and other breeding approaches (Barlow et al., 2015; Bhandari et al., 2017) to seasonal and short-term weather forecasts (Mhlanga-Ndlovu and Nhamo, 2017) and a better understanding of CMs to support planning (Iizumi and Ramankutty, 2015) (see also Annex B). However, additional costs associated with each of these measures will reduce gross margins (Mandryk et al., 2017) and cropping systems and regions with poor economic performance will remain vulnerable (Diogo et al., 2017). Even at present, the capacity to implement improvements is often limited (Siderius et al., 2021; Thamo et al., 2017). These challenges require coordination between science, policy and practice and interdisciplinary engagements to identify, develop and promote effective coping and adaptation technologies and user-relevant support mechanisms to reduce vulnerabilities specific to particular places and moments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was carried out as part of the Himalayan Adaptation, Water and Resilience (HI-AWARE) consortium under the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA) with financial support from the UK Government's Department for International Development and the International Development Research Centre, Ottawa, Canada. We also thank Annemarie Groot, of Wageningen Environmental Research in the Netherlands, for providing valuable comments to an earlier draft.

Disclaimer

The views expressed in this work are those of the creators and do not necessarily represent those of the UK Government's Department for International Development, the International Development Research Centre, Canada or its Board of Governors.

Annex A. . Inclusion and exclusion criteria, and methods for searching literature

No.	Documents included dealing with ...	Documents excluded dealing with ...
1.	Analytical relevance - Climate and weather - Temperature (min/ max, day/night, intra-seasonal, intra-annual, by crop stage, heat stress, consecutive min/max temperature) - Rainfall (intra-seasonal/intra-annual precipitation variability, variability in runoff for supplemental irrigation, seasonal drought/ flooding) - Trends and variability (probability of occurrence) of rain, temperature, change in intensity	Analytical relevance - Climate and weather - Mean climate changes - Climate variability not specific to crop stage - Non-climatic drivers - Inter-annual and long-term trends with no indication or discussion of intra-annual weather changes
2.	Theoretical perspective and methods used - Climate models (top-down, projection of weather variability (intra-annual) and discussion of seasonal changes or changes in a certain crop stage) - Crop simulation models focusing on a stressor(s) at a certain crop stage or stages - Agronomy (field trial identifying stress level at a specific time and associated yield risk) - Vulnerability (bottom-up field level studies measuring crop-related impacts at farm, household or community level; discussion of level of losses, changes in practices and conflicts in crop management practices due to weather or variability during the crop season) - Econometric models (analysing impacts of variations in weather variables by crop stage, biophysical factors, perceptions and field experiences) - Direct (changes in yield) and indirect impact (change in insects, pests, etc.) on crops due to weather variability - Positive or negative impacts on yield	Theoretical perspective and methods used - Climate models (top-down, projection of inter-annual and decadal variability in general, no discussion of crop stage or discussion linked to non-crop sector) - Crop simulation models (not focused on individual hazard to crops at specific time) - Agronomy (not focused on climate and weather variability) - Vulnerability (bottom-up field level studies measuring impacts other than crop at household or community level) - Econometric models (analysing impact not specific to crops at seasonal level) - Long-term shifts in cropping system or management practices due to shift in mean climate conditions - Market and price impacts, even due to weather variability at certain crop stage - Vulnerability to extremes
3.	Type of studies - Peer reviewed journal article - Book chapters, research reports, doctoral theses, institutional technical reports (IPCC, World Bank, FAO, CGIAR and other research institutes)	Type of studies - Non-peer reviewed journal article - Reports from non-research organizations, NGOs and newspaper articles
4.	- Spread -Global (regional, country, zone, field level)	
5.	Language - English	Language - Non-English
6.	Time period published - 1985 and onward	Time period published - Before 1985
7.	Coverage - Crops in general, wheat, rice & maize in particular	Coverage - Other than crops
Method	We searched for and screened the relevant literature using keywords, phrases, Boolean and proximity operators, consulting different databases including the Web of Science, EBSCOhost and Ovid. The snowball technique was used to identify further literature on specific aspects like crop stage, hail, workability, etc. The relevant literature was reviewed focusing on garnering evidence on the concept of CM, synthesis of examples for different types of CMs and associated factors other than yield that lead to vulnerability.	

Annex B. . Summary of different types of CMs and general recommendation from the examined literature.

Type of CM	Hazard	Time period/crop stage & pathways	General recommendations proposed to deal with shifting and changing CMs
Immediate Impact CM	Dry/wet season	Sowing: Workability issue, cost, late sowing & shorter growing season, seed potato vigour loss	Identify key climatic risks to production using long term crop and weather observations; The Netherlands (Van Oort et al., 2012); Risk assessment using Agro-climate calendar by crop stage (Schaap et al., 2011)
	Low temperature	Germination: Frost, seedling death or advanced senescence	Greater understanding required for impacts of extreme by duration and compound impact of heat/frost interaction with other abiotic stresses (moisture stress), Wheat-review, (Barlow et al., 2015)
	Low temperature T. extremes	Vegetative: Seedling survival, leaf damage, soil-borne diseases, poor crop establishment	Genetic improvement, Wheat, (Barlow et al., 2015); Agronomic and breeding approaches, Food legumes, (Bhandari et al., 2017); Chickpea, Inclusion of heat tolerant genes in varieties for warmer areas (Devasirvatham et al., 2013)
		Vegetative: Seedling death, stunted growth, increased susceptibility to diseases, Heat/chilling shock in broad bean reduce growth and quality	Improved breeding and agronomic management, Food legumes, (Bhandari et al., 2017); Broad bean, heat/ chilling shock (Hamada, 2001); Full impact require assessment of combine & multiple impacts over crop season; Wheat, (Porter and Gawith, 1999)

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(*continued*)

Type of CM	Hazard	Time period/crop stage & pathways	General recommendations proposed to deal with shifting and changing CMs
	High temperature, Heat stress, T. extremes	Reproductive: Yield and quality loss (protein concentration decreases),	Predictive capability of crop models to incorporate grain quality for adaptation strategies; Wheat, (Nuttall et al., 2017);
		Maturity/ Ripening (lodging, yield & quality loss)	Lodging resistance variety through breeding, selection for a root system with high anchorage strength; Canola, Canada, (Wu and Ma, 2018)
		Reproductive: low yield	Improve crop management; Rainfed maize, USA (Lobell et al., 2013); Develop heat tolerant varieties; Rice, South Asia, (Wassmann et al., 2009b)
		Reproductive and grain filling: low yield, affect composition of protein and starch (quality),	Further studies on quality and chemical changes; Maize-Argentina (Mayer et al., 2016); Develop short duration stress tolerant varieties; Wheat, Indus delta (Rasul et al., 2012)
		Reproductive and maturity: Higher probability, forced maturity	Quantify future impacts, after heading tolerant varieties, cultivars with earlier heading; Wheat, China (Liu et al., 2014a); Geo-spatial vulnerability assessments for targeted adaptation, Rice, S. Asia, (Wassmann et al., 2009a)
		Reproductive (grain filling): higher probability & variability, sterility, grain shrivelling, affect quantity and quality, pest and diseases, yield and quality, in chickpea abortion of flowers, pods and impaired seed filling in chickpea	Quantify probabilities of extreme events; Legumes, maize, rice, (Luo, 2011); Coupling physiological responses with genetic traits; Maize, sorghum, cotton, rice, bean, soybean and wheat, (Hatfield et al., 2011); kidney bean, USA , (Prasad et al., 2002), Cotton, USA, Short period stress tolerant varieties (Reddy et al., 1992) Explicit modelling for impact on grain formation stage; Wheat, (Porter and Gawith, 1999); Genetic improvement; Wheat, rice, maize, (Tripathi et al., 2016); Genetic improvement, land use changes and water management, Crops, USA (Wienhold et al., 2018); Genetic selection & improvement; Food legumes, (Bhandari et al., 2017); Chickpea, sucrose mobilization and its utilization in the seeds for developing cold tolerance (Kaur et al., 2008), Rice, Philippines (Shi et al., 2017); Incorporation of time of exposure in the yield impact model; Wheat, (Barlow et al., 2015); Identification of heat tolerant varieties (Talukder et al., 2010); Research on combined effect of extreme events on grain set; wheat, (Porter and Gawith, 1999); Early warning system; Winter crops, Australia (Shen et al., 2018)
	Heavy rains	Vegetative (Submergence)	Submergence-tolerance traits, rainfed rice, Bangladesh, (Wassmann et al., 2009a)
	Wind & rain	Vegetative to maturity, lodging	Planting density and method, fertilizer use and genotype affects lodging, wheat, Ireland (Easson et al., 1993)
	Less rain (Dry spell)	Reproductive & Grain filling: higher dry spell probabilities, most sensitive stage, reduction in the rate of net photosynthesis, and poor grain set and grain development	Development of appropriate cultivars, Grain legumes, arid and semiarid tropics (Farooq et al., 2017)
	Unseasonal rain (heavy rains) Hailstorm	Maturity/harvesting: Anaerobic condition rotting, Pre-harvest sprouting, quality and value, wet fields, workability, cost, delay harvest, soil compaction, rotting of tubers, no harvest	Increase permeability of sub-soil and drainage, Potato Netherlands (Schaap et al., 2011; Schaap et al., 2013); Improve pre-harvest sprouting tolerance in cultivars, White wheat Australia, South Africa, Canada, Central Asia and Europe (Biddulph et al., 2008); Weather forecast, Sugarcane, Swaziland (Mhlanga-Ndlovu and Nhamo, 2017); Identify key seasonal climatic risks, Potato, The Netherlands (Van Oort et al., 2012)
Compound Impact CM	Unseasonal rain (Wet or dry season)	Sowing/transplanting; higher probability of exposure to extreme events later in the season	Develop yield prediction model combining crop calendar model with crop growth model as a function of water availability; Rice, North-east Thailand (Sawano et al., 2008)
	Low rain and frost Moisture and heat stress High humidity (rain), wind	Reproductive & grain filling, sterility, low yield, Pest outbreak (two spotted spider mites on soybean), high cost, Synergistic effect on photosynthetic process of both high or low temperature under moisture stress, feed value	Innovative strategies through coordinated efforts of geneticists, agronomists, and agricultural meteorologists, Maize, USA (Hatfield et al., 2018); Cereals, (Wang and Frei, 2011); Location specific response crop climate models, projections based crop movement to future higher production regions; Maize, USA (Westcott et al., 2005); Breed improvement using genetic maps based on molecular marker, expression profiling for interactive tolerance, proteomic studies and genomic approaches along with field evaluation; Cereals, (Barnabas et al., 2008); Wheat varieties resistant to high temperature Wheat, USA (Shah and Paulsen, 2003)

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Type of CM	Hazard	Time period/crop stage & pathways	General recommendations proposed to deal with shifting and changing CMs
	Low rain & frost Moisture & heat stress	Reproductive: viability of pollination	Identify morphological traits associated with tolerance to stress, stress tolerant varieties, Rice, (Tripathi et al., 2016); (Matsui et al., 2005);
	High humidity (rain) & wind	Reproductive: Lodging	Strengthening the stem and the anchorage system by exploiting the wide genetic variation in plant characters and through crop management decisions, Cereals, (Berry et al., 2004);
	High temperature and humidity	Reproductive: spikelet sterility	Target breeding environments into hot and humid versus hot and dry zones and tailor the selection protocols Rice, (Wassmann et al., 2009b); (Shah et al., 2011);
	Wind & rain	Different stages: increase in risk, disease, lodging, management issues, pests and pathogen, disease due to moisture stress, mycotoxin with rains, post production quality issues	Extreme probability based planning, impact analyses with multiple extremes; wheat, Europe (Trnka et al., 2014); Crop stage and region-specific strategies; Arable crops, Europe, (Trnka et al., 2015); incorporating heterogeneity into crop and risk mitigation processes, deploying cultivars multiple resistance genes; Crops, Brazil, Uruguay, Argentina and the UK; (Chakraborty and Newton, 2011)
	Two moderate extremes (different stages)	Different stages: Higher frequency, decrease in gross margins & total NPV, threaten future economic viability of Dutch arable farming)	Crop and farm (diversification) targeting farm economics considering; Seed onion, potato, wheat and sugar beet Flevoland, the Netherlands (Mandryk et al., 2017); Scenario based prioritising adaptation strategies; Arable farming, the Netherlands (Diogo et al., 2017)
	Unseasonal rain & storm	Harvesting (rice), sowing/grain formation (wheat): wet field, land preparation, sowing, heat stress	Development of early maturing rice and heat tolerant wheat varieties (Krupnik et al., 2015)
	Extreme weather events	Different stages - Crop area & intensity	Impact assessment for less studied extreme weather events on crop area, intensity, and production, changes in the work calendar and field workability considering farmer responses within different economic conditions and access to technology for developing climate-resilient crop production systems; Crops, (Iizumi and Ramankutty, 2015)
Shifted impact	Heavy rain	Harvesting (Wet field – inability to harvest, workability issue, higher cost, quality loss)	Maintain good soil quality & structure matters, Wheat-Netherlands (Schaap et al., 2011);

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