ORIGINAL ARTICLE

Mapping agricultural vulnerability to impacts of climate events of Punjab, Pakistan

Faisal Nadeem[1] · Brent Jacobs[1] · Dana Cordell[1]

Abstract

Pakistan has an agriculture-dependent economy vulnerable to climate impacts. Within Pakistan, Punjab province is a leading regional producer of food and cash crops, and an exporter of agricultural commodities of significance in South Asia. Punjab agriculture provides livelihoods for agriculture-dependent communities living in one of the most populous countries of the world and these will be disrupted under incremental climate changes (e.g. rising temperatures) and the impacts of extreme climate events (such as droughts and floods). Climate impact assessments and mapping are widely accepted initial approaches to address climate change as they have the potential to facilitate bottom-up adaptation. However, to date, policy responses in Pakistan have tended to be top-down, driven by national adaptation planning processes. This paper assesses agricultural vulnerability to impacts of climate events at the district scale for Punjab province by developing maps of the individual components of vulnerability, i.e. exposure, sensitivity and adaptive capacity. An indicator-based approach using a composite index method was adopted for the assessment. The mapping separated and categorised districts in Punjab based on their vulnerability to climate change and revealed spatial patterns and factors influencing district-level vulnerability. These geospatial variations in vulnerability illustrate the need for a nuanced policy on adaptation that recognises the importance of local biophysical and socio-economic context to build adaptive capacity for vulnerable regions rather than the current concentration on broad-scale top-down action embedded in National Adaptation Plans.

Keywords Vulnerability assessment · Mapping · Impacts of climate events · Agriculture · Punjab

Introduction

Climate change is a global problem with potentially wide-ranging effects (IPCC 2007, 2014) that are not uniformly distributed globally and vary spatially. Agriculture is recognised to be highly climate sensitive (Howden et al. 2007) and this sensitivity is projected to rise with future climatic changes (FAO 2009; Li et al. 2015). In particular, the effects of climate change on agriculture are concerning for

developing countries where livelihoods of vast populations depend heavily on outcomes from farming, both subsistence and commercial (Patt and Klein 2012; Maharjan and Joshi 2013). Global and local studies indicate that Pakistan, an agriculture-dependent developing country, is among the most vulnerable nations to the impacts of climate events owing to its limited coping capacity (Kelly et al. 2005; TFCC 2010; Barr et al. 2010). Pakistan's agriculture contributes 24% of GDP and 60% in foreign exchange earnings to the national economy (PBS 2020). Furthermore, nearly three-quarters of Pakistan's population has direct or indirect dependence on agriculture, which employs around 46% of the total labour force (Rehman 2016).

Within Pakistan, Punjab province dominates the nation's output of major staple crops including food crops (wheat, rice and maize) and cash crops (cotton and sugarcane). It has a leading role in national food production by contributing 74% to the total cereal production of the country (PBS 2020) and is not only a national food bowl but is also an important exporter of agricultural produce

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(Noorka and Shahid 2013). For instance, Punjab is a major contributor to global rice exports and is one of the few cotton-producing regions of the world (Rehman et al. 2015; Yuansheng et al. 2016).

The effects of climate change threaten agriculture in Punjab. Analyses of long-term temperature trends indicate the region is experiencing a warming pattern (Abbas 2013; Penas et al. 2016). Future projections show that the increase in average annual temperature in Punjab is likely to be above the global average by 2100 (GCISC 2005; Salik et al. 2015). Crop production in Pakistan is vulnerable to the impacts of climate events (TFCC 2010). For instance, wheat crop yield in Pakistan would likely decrease by about 4–5% for each 1 °C rise in temperature (GCISC 2005). Also, already stressed surface water availability is expected to be further reduced with climatic changes which have potential implications for crop irrigation in Pakistan (Qureshi 2011). In addition, increased incidence of crop pests is likely in the warm climate and a growing problem in all cotton-growing areas of Pakistan (Bakhsh et al. 2005). Moreover, Punjab province has experienced an increase in floods in recent decades with damage to the economy. For example, direct losses from floods for the 2010–2017 period were estimated to exceed US$18 billion (Federal Floods Commission 2018). Therefore, climate change not only acts as an amplifier of agricultural vulnerability in Punjab province (e.g. Scheffran 2015) but also poses direct serious challenges to the livelihoods of poor, agrarian communities.

Adaptation to the impacts of climatic events has the potential to reduce vulnerabilities of communities through adjustments in processes, structures and practices (Smit and Pilifosova 2003), and is significant because ongoing change is 'locked in' to the climate system from past greenhouse gas emission (Patt and Klein 2012). As a policy response to climate change, the national government of Pakistan has formulated a range of strategies including the National Climate Change Policy 2012 (NCCP 2012). These broad policy documents tend to be mitigation—rather than adaptation—centred, which is common to the policy responses of many developing countries (Holler et al. 2020). However, the current policies emphasise the need for climate vulnerability assessments and mapping of impacts, widely accepted as early approaches to address climate change due to their potential to facilitate bottom-up adaptation by tailoring local adaptation plans and measures in accordance with local requirements (Patt and Klein 2012; Malone and Engle 2011). Vulnerability mapping is considered beneficial for targeting adaptation assistance (e.g. Sherbinin et al. 2017) because climate variability and extremes, the sensitivity of populations to climate-induced stressors and capacities to adapt vary spatially. The role of multivariate geographic visualisation in vulnerability mapping (Opach

and Rød 2013; Wiréhn et al. 2017) has the potential to serve as a knowledge management tool for decision-makers to guide adaptation action (Sherbinin et al. 2017; Opach et al. 2020).

Despite differences in scope, methodology and geographical aspects, other vulnerability assessments in Pakistan also differ from the current study in research focus. To date, assessments of vulnerability in Pakistan have focused on themes including human health (Malik et al. 2012), social impacts (Rahman and Salman 2013), coastal geographies (Salik et al. 2015), gender (Iqbal et al. 2015), water resource (Shabbir and Ahmad 2016) and natural hazards (Rafiq and Blaschke 2012; Khan and Salman 2012; Zahid and Rasul 2012; Ghazal et al. 2013; Mazhar and Nawaz 2014; Ashraf and Routray 2015; Zuhra et al. 2019; Qaiser et al. 2021). Few vulnerability assessments have reflected the importance of agriculture-related themes per se. For instance, a gender-focused study included the objective of exploring gender- and age-differentiated factors on household vulnerability and food security (Iqbal et al. 2015). Another drought-focused study on Karachi city of Sindh province aimed to explore changes in agricultural patterns in response to the food demands of the inhabitants (Ghazal et al. 2013). However, vulnerability assessments and mapping have rarely focused comprehensively on the agriculture and major crops sector, particularly at the provincial scale. Our purpose in conducting the vulnerability assessment reported here, which is based on a top-down approach employing secondary sources of data, was to identify the districts most vulnerable to the impacts of climate events to guide further place-based studies, rather than seeking to develop definitive policy responses for the national government. This study focused specifically on the assessment of adaptive capacity, a component of vulnerability, because we sought also to inform local action on climate impacts (Jacobs et al. 2015). Although biophysical factors (i.e. temperature, rainfall variability and climate extremes such as floods and droughts) play an important role in shaping exposure to climate variability and change in Punjab, district and provincial policy actors are unable to directly influence them, as they are driven by global changes in atmospheric levels of greenhouse gases. In contrast, and while recognising limitations (e.g. Thomas et al. 2021), these local actors can influence capacity-building interventions for reducing vulnerability. Thus, in keeping with the current policy setting and to address the gap in the literature, this paper aims to assess agricultural vulnerability to impacts of climate events by mapping exposure, sensitivity and adaptive capacity (i.e. the components of vulnerability, McCarthy et al. 2001; Patt and Klein 2012) for the Punjab province to inform future action on adaptation.

Fig. 1 Location of the Punjab province (blue shading) within Pakistan and other nearby countries

Method

Study area

The study was conducted on the Punjab province of Pakistan (Fig. 1). Punjab is the largest province by the population of 110 million and the second largest province in terms of area, covering 205,345 sq. km (PBS 2020). Punjab accommodates over 50% of Pakistan's population and produces over 60% of total national agricultural commodities (Abbas et al. 2014; PBS 2020).

Administratively, Punjab province is divided into 36 districts. In general, Punjab province has long hot summers and cold winters. Rainfall in Punjab is mostly related to the *monsoon* winds. According to the Pakistan Meteorological Department climate classification of Pakistan, Punjab province includes the climate classifications of extremely arid, arid, dry semi-arid, wet semi-arid, wet sub-humid and dry sub-humid (PMD 2021). The combination of seasonal temperatures and rainfall divides the agricultural calendar into two major cropping seasons, *Kharif* (summer) and *Rabi* (winter). Rice, cotton, maize and sugarcane are major *Kharif* crops while wheat is a major *Rabi* crop (Hussain and Mudasser 2007; Naheed and Rasul 2010).

Data sources

The data collection for the study relied on secondary data sources available through the Government of Pakistan, including the Bureau of Statistics (BOS) Punjab, Pakistan Meteorological Department (PMD) and National Disaster Management Authority (NDMA). The meteorological data on temperature and rainfall (2005–2015) were obtained from PMD for all meteorological stations of Punjab province. Obtaining metrological data from government sources was given priority since it was 'cleaned' data after removal of any errors and comes through sources considered official and reliable. Most of the districts of Punjab have only a single meteorological station, while a few districts do not have their own meteorological station. Where a district lacked a meteorological station, the closest station data was taken for calculating temperature and rainfall indicators. Flood exposure data was estimated from NDMA. Secondary data for all sensitivity and adaptive capacity indicators for years (2010–2015) were obtained from BOS official publication reports of annual Punjab Development Statistics from 2012 to 2016 (Pakistan Economic Survey 2010–2011, 2011–2012, 2012–2013, 2013–2014, 2014–2015).

Methodological framework

The methodological framework for the study involved several key steps (Fig. 2):

Step 1: Approach

To assess agricultural vulnerability to impacts of climate events of Punjab province, an indicator-based approach was adopted because it offers several related advantages over alternative approaches, such as risk hazard, entitlements and ecological resilience approaches, and is well aligned with the objectives of this research. Indicator-based approaches are widely used in vulnerability studies (Eriksen and Kelly 2007; Li et al. 2015) because they have the potential to accommodate a range of units of analysis together and enable comparative analysis of vulnerability (Malone and Engle 2011). When mapped, they are a useful tool to communicate research findings to a wider audience including policy decision-makers and can be used as a basis for deeper analysis (O'Brien et al. 2007; Malone and Engle 2011; Patt and Klein 2012; Opach and Rød 2013; Wiréhn et al. 2017). Indicator-based approaches have been extensively applied to a range of situations including disaster vulnerability in India (Chakraborty and Joshi 2016), farming sector vulnerability to climate change and variability in South Africa (Gbetibouo and Ringler 2009), agriculture sector vulnerability in Australia (Nelson et al. 2010) and coastal communities' vulnerability to floods in Ghana (Yankson et al. 2017).

Step 2: Selection of indicators

The selection of all indicators was informed by a review of their use in the literature and, pragmatically, based on the availability and quality of secondary data. Indicators, defined as variables, are an operational representation of an
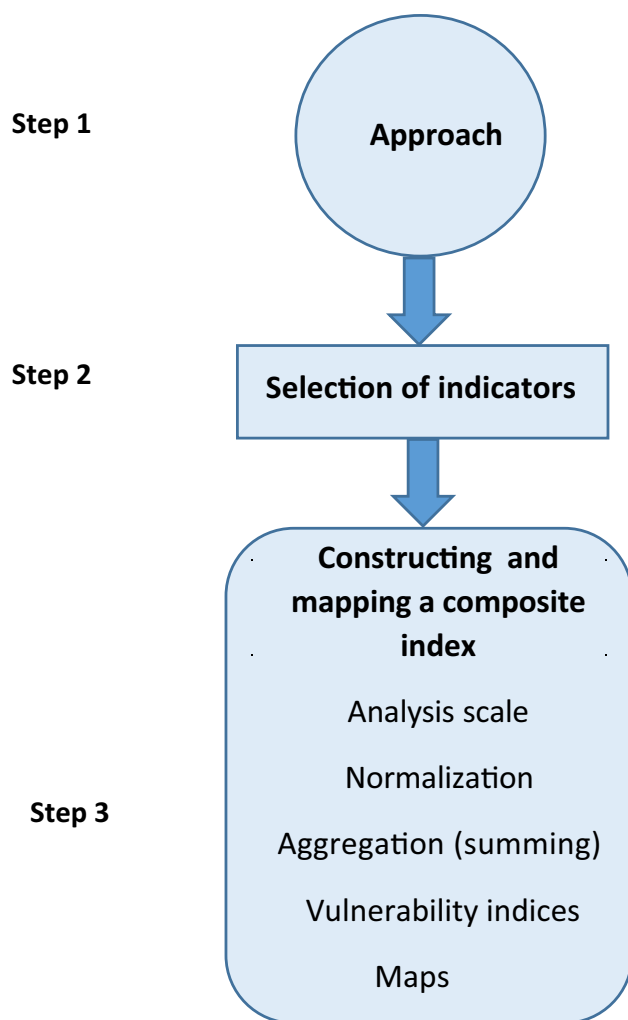
Fig. 2 Methodological framework

attribute (Birkmann 2006; Gallopín 2006). The initial step in their selection was to identify indicators relevant to the current study and categorise these for their representativeness of the dimensions of vulnerability. The term vulnerability has been used in the literature in a variety of ways (Cordell and Neset 2014; Füssel and Klein 2006) and is generally defined as 'the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes' (McCarthy et al. 2001 pg. 995). Vulnerability is commonly conceptualised as three components, i.e. exposure, sensitivity and adaptive capacity (IPCC 1996; McCarthy et al. 2001), and this conceptualisation was adopted in this study. Exposure is considered as an entry point to the concept of vulnerability (Smit and Wandel 2006). Exposure is defined as 'the nature and degree to which a system is exposed to significant climatic

variations' (McCarthy et al. 2001 pg. 987). Like exposure, sensitivity is also directly associated with vulnerability. Sensitivity is defined as 'the propensity for exposure to result in harm' (Jacobs et al. 2014). Selected exposure and sensitivity indicators for this study with the justification for their use are shown in Table 1.

Contrary to exposure and sensitivity, adaptive capacity is inversely associated with vulnerability. Adaptive capacity in the context of climate change is defined as 'the ability of a system to adjust to climate change including climate variability and extremes to moderate potential damage, to take advantage of opportunities or to cope with the consequences' (McCarthy et al. 2001 pg. 982). The development of an index of adaptive capacity drew on the theory and practice of the rural livelihoods analysis (Bebbington 1999). The rural livelihoods framework as conceived by Ellis (2000) conceptualises adaptive capacity as comprising different forms of natural, social, financial, physical and human capitals (e.g. Nelson et al. 2005). These capitals have potential significance in shaping respective adaptive capacity and livelihood outcomes due to the flexibility of substitution and inter-conversion between them at times of stress, including extreme weather events such as floods and droughts (Ellis 2000). Rural livelihoods analysis has been used for assessing adaptive capacity in both developed and developing countries (Ellis and Freeman 2005; Nelson et al. 2010) and it can be applied by using indicators and indices (Jacobs et al. 2015). The rural livelihoods analysis can be carried out at a range of scales and is particularly useful as a guide to policies in rural areas (Ellis 2000). With the view of applications in developing countries, and scale, flexibility and alignment with the indicator approach adopted for this research, a livelihoods approach was considered suitable for assessing adaptive capacity as part of vulnerability assessment in Punjab province. The selected adaptive capacity indicators with justification for their use are shown in Table 1.

Step 3: Constructing and mapping a composite index

Identification of *analysis scale* is considered one of the early steps of index construction (Tate 2012). Sub-national level (i.e. district administrative boundaries of Punjab province) was taken as the *analysis scale* for index construction. This scale was chosen because of the availability of more reliable secondary data and to allow a comparison of the relative vulnerability of districts.

The *functional relationship* of each potential indicator with vulnerability was established from the literature since vulnerability can be increased or decreased with a change in an indicator (Table 1). Indices for each of the dimensions of

Table 1 Exposure, sensitivity, adaptive capacity indicators

Dimensions	Variables	Indicators* (units)	Functional relationship to vulnerability	Data sources	Justification (references)
Exposure	Annual temperature	Coefficient of variation COV-temperature (mean, range, standard deviation) (degree Celsius)	Direct	Pakistan Meteorological Department (PMD) Government of Pakistan	Temperature and rainfall variability each has a direct functional association with agricultural vulnerability (Gbetibouo & Ringler 2009; Ravindranath et al. 2011)
	Annual rainfall	Coefficient of variation COV-rainfall (mean, range, standard deviation) (millimetre)	Direct		
	Floods	Houses damaged by flood 2010 megaflood (number)	Direct	National Disaster Management Authority (NDMA), Government of Pakistan	The floods adversely affected vast areas of the country including the fertile agricultural lands of Punjab province with direct and indirect economic losses (Federal Floods Commission 2018), selected as a proxy for the area's agricultural exposure to floods
Sensitivity	Irrigated land	Irrigated to the non-irrigated area (percent)	Inverse	Punjab Development Statistics, Bureau of Statistics (BOS) Punjab, Government of Punjab	Irrigated land has a positive association with enhanced agriculture production, and in turn, higher agricultural productivity has positive effects on the livelihoods of agricultural communities (O'Brien et al. 2004; Ravindranath et al. 2011)
	Population in administrative jurisdiction	Population density per district (persons per square kilometres)	Direct		Higher population density require greater humanitarian assistance due to more people facing extreme climatic events (Gbetibouo & Ringler 2009)
	Cultivated land	Sown area share in total area (percent)	Direct		Greater area under cultivation is the likelihood to be more sensitive to climatic variations (Chakraborty & Joshi 2016; Ravindranath et al. 2011)
	Farm size	Share of small farm holdings in total holdings (percent)	Inverse		Small farms are less likely to adopt agriculture technologies due to larger associated costs (Daberkow & McBride 2003; Tey & Brindal 2012)
	Crop diversification	Area sown more than once annually (hectares)	Inverse		Higher crop diversification is likely to improve the resilience of agriculture systems in several ways, e.g. create greater ability to suppress pest occurrences, reduce pathogen transmission (Lin 2011; Gbetibouo & Ringler 2009)
Sensitivity	Agroforestry potential	Total forest area (hectares)	Inverse	Punjab Development Statistics, Bureau of Statistics (BOS) Punjab, Government of Punjab	Agroforestry potential improves farm productivity by reducing soil erosion and improving soil fertility (Thorlakson & Neufeldt 2012; Verchot et al. 2007)
Adaptive capacity (human capital)	Literacy level	Adult literacy rate (percent)	Inverse		Educated farmers can better understand and participate in technological and administrative processes than farmers with little or no formal education (Adejuwon 2008; Deressa et al. 2009)
	Health attainment	Hospitals, rural health centres, basic health units and dispensaries (number)	Inverse		Increases in health care expenditure are associated with large improvements in health outcomes including decreased infant mortality rates (Nixon & Ulmann 2006; Berry et al. 2011)
Adaptive capacity (financial capital)	Livelihoods diversification	Registered factories (number)	Inverse		Non-farm income increases the likelihood of adaptation options (Deressa et al. 2009)
	Access to credit	Financial institutions (number)	Inverse		Adoption of agricultural technologies requires sufficient financial well-being (Knowler & Bradshaw 2007; Deressa et al. 2009)
	Livestock ownership	Work animals (number)	Inverse		Livestock ownership is positively correlated with the number of adaptation options (Yirga & Hassan 2010; Deressa et al. 2009)
Adaptive capacity (social capital)	Access to cooperative societies	Membership of cooperative societies (number)	Inverse		Cooperative social networks promote information exchange and cooperation that help communities adapt to climatic changes (Gbetibouo & Ringler 2009; Cinner et al. 2018)
	Means of social support	Share capital (rupees in million)	Inverse		Sharing capital as social collaboration initiatives are dimensions of social capital (Bijman et al. 2011)
	Local committees access	Local zakat committees (number)	Inverse		Committees as social networks have the potential to facilitate bridging social capital and also act as conduits for financial transfers that may ease the farmer's credit constraints (Woolcock & Narayan 2000; Cinner et al. 2018; Gbetibouo & Ringler 2009)

Table 1 (continued)

Dimensions	Variables	Indicators[*] (units)	Functional relationship to vulnerability	Data sources	Justification (references)
Adaptive capacity (natural capital)	Groundwater availability for agriculture	Tube wells (number)	Inverse	Punjab Development Statistics, Bureau of Statistics (BOS) Punjab, Government of Punjab	Areas with more groundwater available for agriculture are likely to be more adaptable to adverse climatic conditions (O'Brien et al. 2004; Ravindranath et al. 2011)
	Land productivity	Fertiliser consumption (tons)	Inverse		Farmers are more likely to adopt any technologies, such as the use of fertilisers, that will help them maintain or improve their productivity (Gbetibouo & Ringler 2009; Ravindranath et al. 2011)
Adaptive capacity (physical capital)	Access to the power supply	Power generation stations (number)	Inverse		Access to electricity supply enables the usage of water pumps required for irrigation and reduces manual labour (Kirubi et al. 2009; Shukla et al. 2016)
	Agricultural machinery ownership	Tractors and threshers used for agriculture (number)	Inverse		There has been strong advocacy for agricultural machinery for farmers to enhance land productivity and resource base (Kienzle et al. 2013; Mottaleb et al. 2016)
	Access to transport networks	length of metalled road (kilometres)	inverse		Accessibility to roads and markets is critical for remunerative agriculture development, access to agriculture inputs and increases the opportunities for non-farm livelihood activities (Sietz et al. 2011; Shukla et al. 2016)

[*]Indicators per district

vulnerability (i.e. exposure, sensitivity and adaptive capacity) were constructed separately for the districts of Punjab province using the Composite Index Method (Vincent 2004). Composite Index Method has been used to calculate social vulnerability (Vincent 2004) and applied to assessments of agricultural vulnerability, e.g. South African Farming Sector Vulnerability (Gbetibouo and Ringler 2009) and agricultural drought vulnerability in the Andhra Pradesh state of India (Murthy et al. 2015). Separate indices of exposure and sensitivity were firstly calculated and combined to represent potential impact (PI). Then, the overall vulnerability index was constructed as the difference between potential impact (PI) and adaptive capacity (AC) and is represented mathematically as:

$$Vulnerability(V) = f(PI - AC)$$

where, *Potential Impact (PI) = exposure + sensitivity*.

Since indicators were measured in a variety of units, *normalisation* of exposure, sensitivity and adaptive capacity variables was performed to obtain standardisation to a relative, dimensionless measurement scale (Tate 2012; UNDP 2013) using min–max linear scaling methodology commonly employed in deductive structural designs (Tate 2012).

Weighting may be assigned to selected indicators to reflect their relative importance (Murthy et al. 2015). The literature includes published studies of composite index construction where weightings have been assigned (e.g. Ravindranath et al. 2011) and others wherein indicating variables were of equal importance, and weightings were not assigned (e.g. O'Brien et al. 2004). In general, the most common approach is the use of equal weights (Tate 2012) and this method was applied here.

Following normalisation and equal weighting, indicators were aggregated for the development of respective component indices. Additive aggregation (summing) of normalised indicators is nearly universally used (Tate 2012) and was applied here. All normalised indicators of exposure, sensitivity and adaptive capacity were aggregated to form the overall index of vulnerability. Finally, separate maps of exposure, sensitivity, adaptive capacity and overall vulnerability were developed for Punjab province.

Results

The exposure, sensitivity, adaptive capacity and vulnerability indices were classified into five categories of vulnerability, i.e. very high (0.80–1.00), high (0.60–0.79), moderate (0.40–0.59), low (0.20–0.39) and very low (0.00–0.19) categories and mapped by districts within Punjab province. The normalisation of aggregate scores brought values within a common range (of 0–1). Accordingly, the districts of Punjab province were ranked into respective vulnerability classifications.

Exposure index

Index values were visualised as a map of exposure for the Punjab province (Fig. 3).
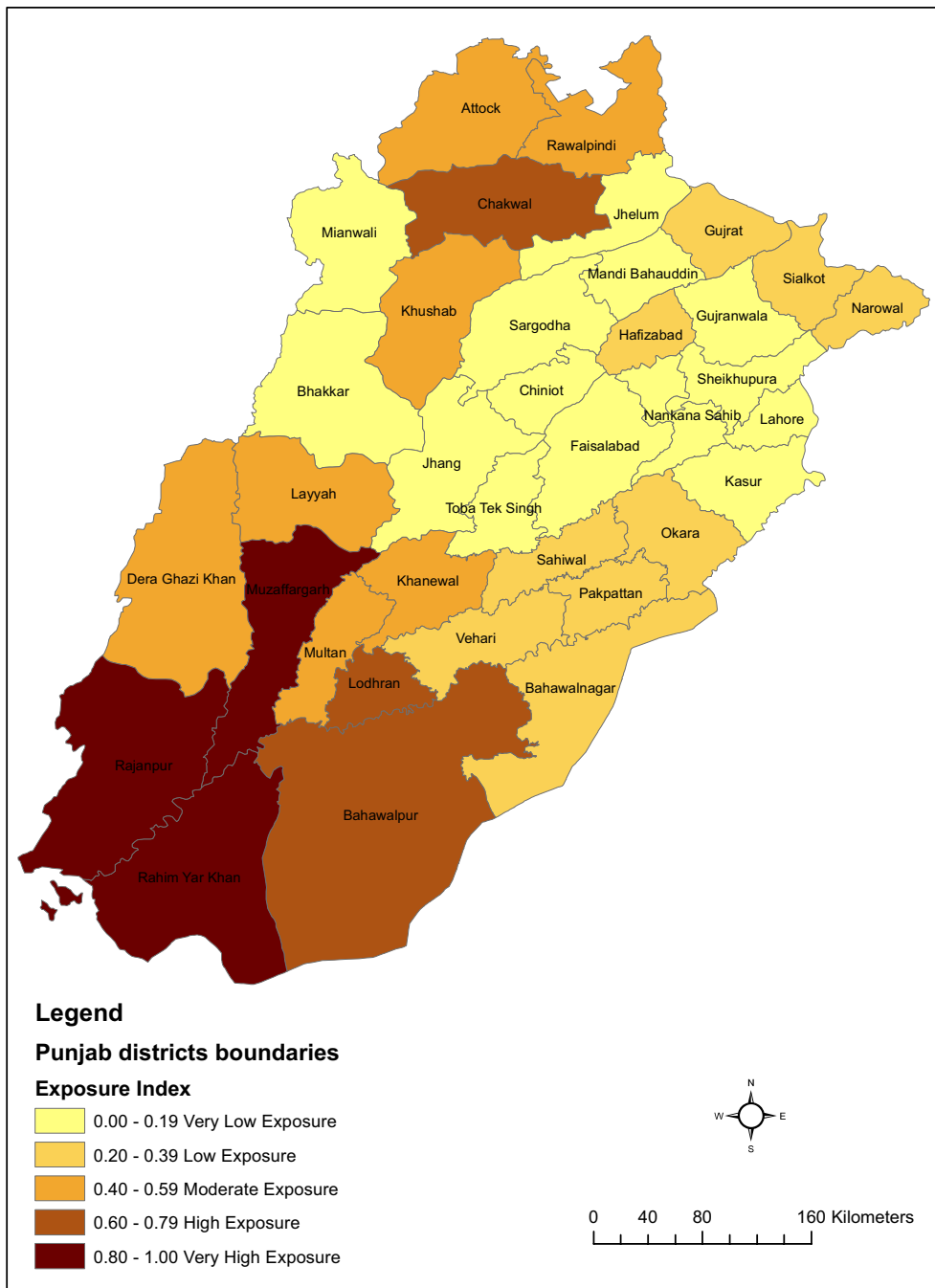
Fig. 3 Map of exposure to impacts of climate events for districts of Punjab province

The exposure mapping separated districts of Punjab into very high to least exposed categories. The exposure map indicates that only three southern Punjab districts, which also share their district administrative boundaries (Rajanpur, Rahim Yar Khan and Muzaffargarh) were classified into the very high exposure category. In contrast, generally most of the central and eastern Punjab districts were categorised into low and least exposure categories.

Sensitivity index

Figure 4 shows the spatial pattern of the sensitivity index in Punjab province.

In contrast to exposure, a group of most sensitive districts (Chakwal, Attock, Jhelum, Rawalpindi, Gujrat) emerged in the north of Punjab. Three low-exposure eastern districts also showed high sensitivity. The central

Fig. 4 Map of sensitivity to impacts of climate events for districts of Punjab province
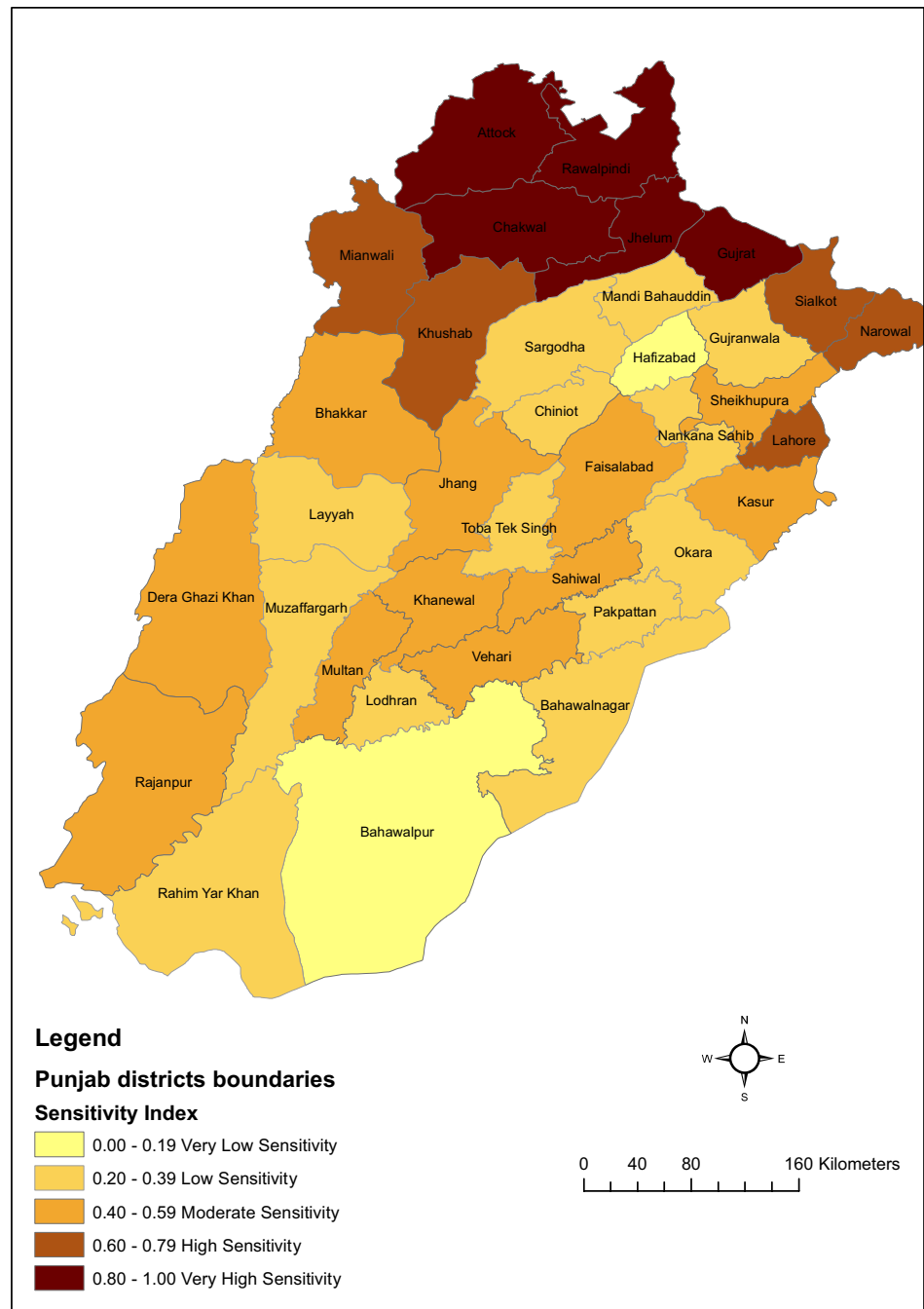
Punjab districts categorised as least exposed showed moderate to low sensitivity. In general, 11 districts were classified as moderately sensitive.
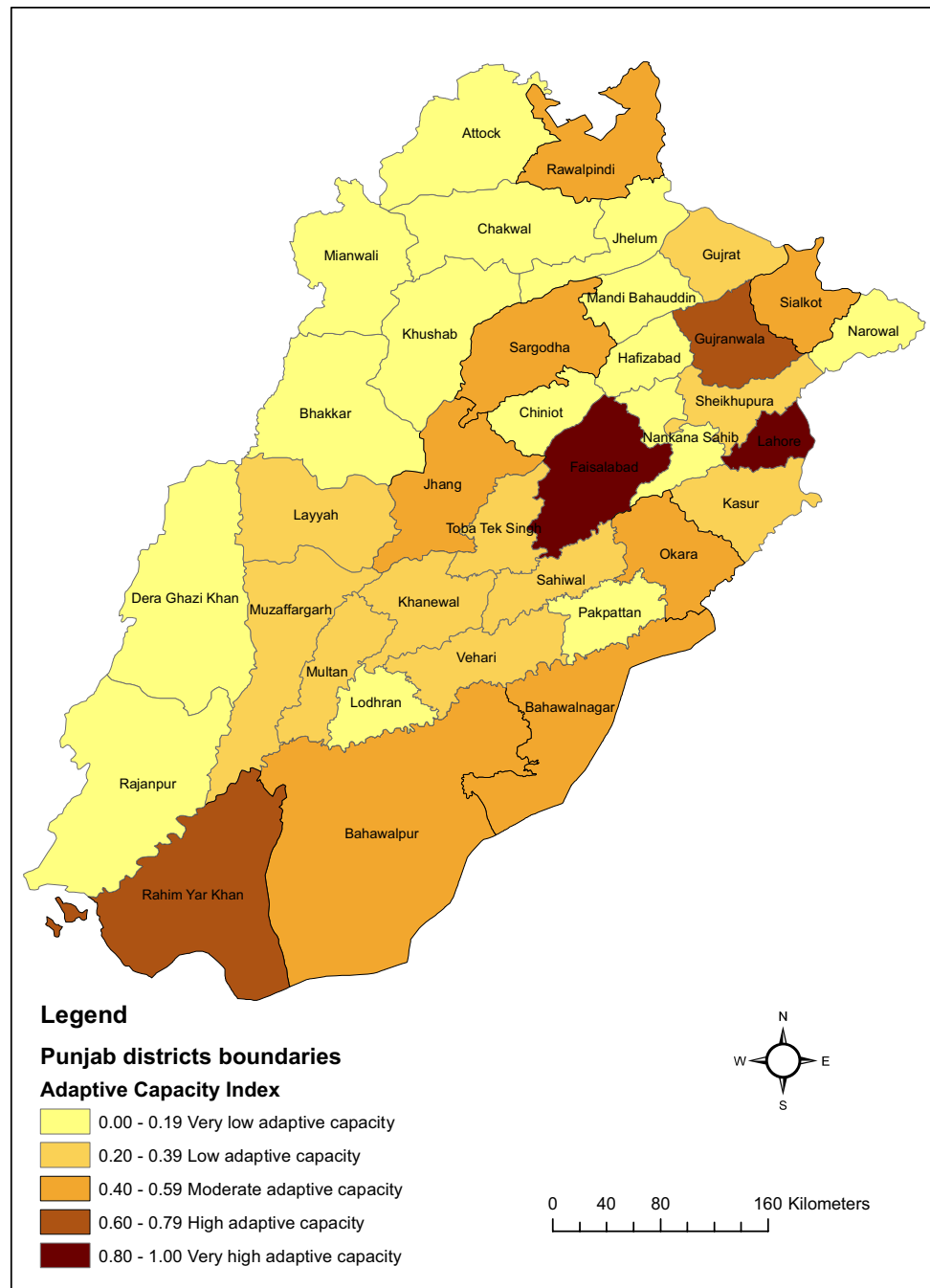
Adaptive capacity index

The map of the adaptive capacity index is illustrated in Fig. 5.

Two high exposure category districts, one in the south (Rajanpur) and one in the north (Chakwal), were classified into the very low adaptive capacity category. Likewise, the three most sensitive category districts in the north (Jhelum, Attock, Chakwal) were also classified under the very low adaptive capacity category, and this is likely to contribute significantly to their vulnerability. However, two very low exposure category districts in the east (Lahore, Faisalabad) were also classified into the very high adaptive capacity category, which will tend to mediate their overall vulnerability. Seven districts (Bahawalpur, Bahawalnagar, Okara, Jhang, Sargodha, Sialkot, Rawalpindi) showed moderate adaptive

Fig. 5 Adaptive capacity map for the districts of Punjab province

Legend

Punjab districts boundaries

Adaptive Capacity Index

▢	0.00 - 0.19 Very low adaptive capacity
▢	0.20 - 0.39 Low adaptive capacity
▢	0.40 - 0.59 Moderate adaptive capacity
▢	0.60 - 0.79 High adaptive capacity
▢	0.80 - 1.00 Very high adaptive capacity

capacity. In general, 10 districts were classified into a low adaptive capacity category and 15 were classified as having very low adaptive capacity.

Correlations among adaptive capacity indicators

To test the association between indicators of adaptive capacity and the developed adaptive capacity index, correlation analysis was performed. The correlations between each of the component indicators and the adaptive capacity index are shown in Table 2.

The analysis indicated that all correlations were significant at ($p < 0.05$). However, some correlations were stronger than others. For example, health attainment (human capital) and local committees (social capital) were most closely correlated with the adaptive capacity index. Other strong correlations included credit access, livelihoods diversification and power access. Literacy level

Table 2 Correlations between indicators of adaptive capacity and the aggregate index

Capital	Indicator	Correlation coefficient	Significance level (P)
Financial	Credit access	.745**	.000
	Livestock ownership	.370*	.026
	Livelihood diversification	.797**	.000
Human	Health attainment	.924**	.000
	Literacy level	.299*	.038
Physical	Power access	.772**	.000
	Agricultural machinery	.549**	.001
	Transport access	.590**	.000
Natural	Land productivity	.448**	.006
	Ground water	.384*	.021
Social	Local committees	.910**	.000
	Means of social support	.600**	.000
	Access to cooperative societies	.806**	.000

**Statistical significance at a 0.01 level

*Statistical significance at a 0.05 level

showed the weakest correlation with the index, although it was statistically significant ($p = 0.038$).

To test for the possibility of multicollinearity issues among the variables, collinearity tests were performed in SPSS to indicate variance inflation factor (VIF) and tolerance values.[1] VIF values of variables were found to be between 1 and 10 while tolerance values were greater than 0.1. These statistics suggest no potential issues with multicollinearity in the correlation analysis results.

Vulnerability index

Figure 6 shows the spatial pattern of vulnerability classes in the study region of Punjab.

The vulnerability map indicates that only five districts (Rajanpur, Muzaffargarh, Chakwal, Attock, Khushab) were classified under the very high vulnerability category. Among these most vulnerable districts, two districts (Rajanpur, Muzaffargarh) are situated in the south and share district boundaries. In contrast, three other most vulnerable districts (Chakwal, Attock, Khushab) are located on the north side of the province and share their district administrative boundaries. Six high vulnerability category districts include four northern districts (Rawalpindi, Gujrat, Mianwali, Jhelum) and two southern districts

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[1] Although there is no single agreed cutoff value for VIF and tolerance to suggest multicollinearity, however, multicollinearity could be suspected with VIF value > 10 and tolerance value < 0.1 (Pallant 2013).

(Dear Ghazi Khan, Lodhran). In general, of the 14 low to very low vulnerability category districts, 10 were low vulnerability districts (eight are in central-east Punjab and two are in southern Punjab), with the remaining four very low vulnerability category districts (Lahore, Faisalabad, Sargodha, Gujranwala) located in east Punjab.

Discussion

Given the agricultural significance of Punjab province, the critical importance of the major crops sector to agriculture and the sensitivity of agriculture to climate, this study assessed Punjab province's agricultural vulnerability to climate change. The key findings arising from this study are:

1. Mapping presented the variation in the pattern of vulnerability and its components, i.e. exposure, sensitivity and adaptive capacity across districts of Punjab.
2. Among the components of adaptive capacity, some aspects of human, social and financial capital were more closely correlated with the capacity for adaptation (e.g. health, local committees and credit) than others (e.g. groundwater access and livestock ownership).
3. Finally, differences in vulnerability illustrate the need for a nuanced policy on adaptation that recognises the importance of local biophysical and socio-economic context. This finding also supports calls for improved linkage between top-down national policy initiatives (such as the National Adaptation Policy) and bottom-up community engagement to support agriculture in Punjab (e.g. Holler et al. 2020).

Variation in Punjab vulnerability

The work of index development differentiated regions in Punjab according to their respective vulnerability to climate change (Fig. 6). Most of the southern and northern Punjab districts were in higher exposure and or sensitivity categories and low adaptive capacity categories. In contrast, most of the eastern and central Punjab districts combined low exposure and or sensitivity with higher levels of adaptive capacity. The study results are relative to the data included in this vulnerability assessment and vulnerability classifications could differ considerably if compared to other regions of Pakistan. Several other studies have developed maps presenting the spatial variations in climate vulnerability focused on other geographical locations, e.g. Australia (Nelson et al. 2010); India (Chakraborty and Joshi 2016; O'Brien et al. 2004) and South Africa (Gbetibouo and Ringler 2009). Considering the breadth of vulnerability research, examples from global vulnerability assessments to climate change in the literature support the aim of this

Fig. 6 Map of vulnerability for the districts in Punjab province
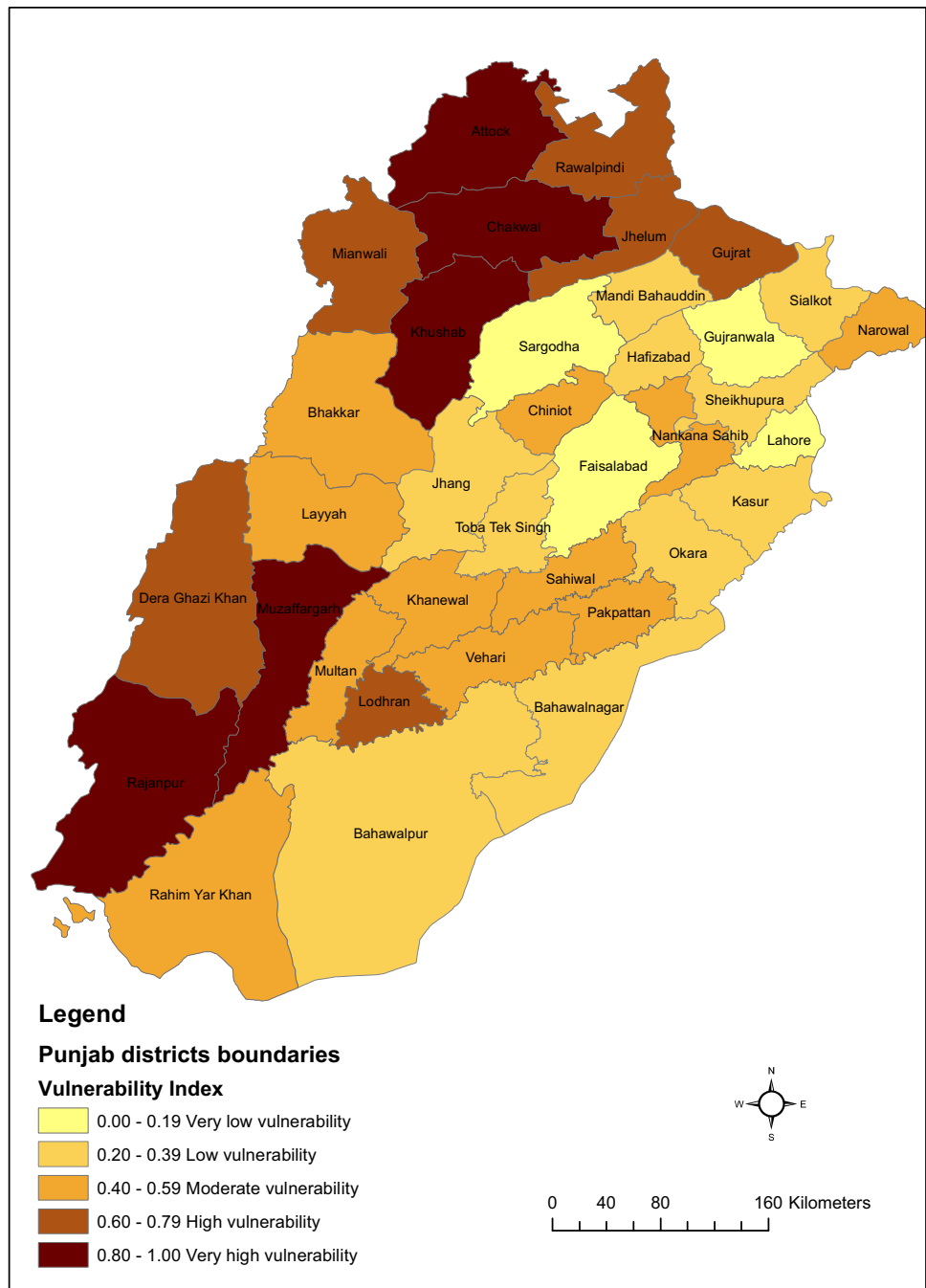
study to guide local action on adaptation. For instance, Gbetibouo and Ringler (2009) noted that large differences in the extent of vulnerability between areas suggest the need to develop region-specific policies. Likewise, Nelson et al. (2010) suggested that to better support adaptation, impact modelling needs to be broadened through the inclusion of options for building adaptive capacity in rural communities. In addition, Chakraborty and Joshi (2016) suggested that vulnerability assessments can assist in identifying and

enhancing the actions required for adaptation strategies for the most vulnerable communities in resource-constrained countries. Such techniques can act as a useful starting point in understanding the dimensions of vulnerability (Malone and Engle 2011) to identify, for example geographical areas where potential adaptation options can be further examined (Malone and Engle 2011; Sherbinin et al. 2017). O'Brien et al. (2004) and Gbetibouo and Ringler (2009) further suggest that it can serve as a basis for targeting policy intervention.

The key features that contributed to the high vulnerability of southern Punjab districts differed substantially from those in northern Punjab. There are several explanations for the spatial variation in vulnerability. Highly vulnerable districts of southern Punjab share many aspects in common among exposure factors, i.e. frequent large floods, observations of elevated average temperatures and frequent drought conditions. Coupled with high levels of exposure, the southern Punjab districts have a very low potential for adaptive capacity due to very low levels of aspects of human, social, physical and financial capitals.

On the other hand, the vulnerable districts of northern Punjab are not prone to flooding, instead, these are *barani* areas where rainfall is the main source of water for agriculture. For these districts, rainfall variability, experienced in its extreme form as prolonged drought, acts as the key climate risk (Qaiser et al. 2021). In addition, northern Punjab districts have a very high proportion of small farms and less crop diversification, making these districts relatively more sensitive to climate change. Furthermore, the high exposure and high sensitivity of these northern Punjab districts are associated with very low adaptive capacity due to several factors related to low levels of human and social capitals and limited opportunities for livelihoods diversification (e.g. Antwi-Agyei et al. 2014).

In contrast, vulnerability maps for eastern and central Punjab districts indicate relatively very low vulnerability to climate change. Most of these districts are not flood prone and also show low sensitivity to climate change due to the extensive availability of irrigation (e.g. Zaveri and Lobell 2019). These factors are moderated to some extent because of the presence of a few large urban centres (the major cities of Lahore, Faisalabad and Rawalpindi) which skew the index towards moderate to high sensitivity, due to very high population density. In addition to low exposure and low sensitivity, most of these eastern and central Punjab districts show moderate to high adaptive capacity, which leads to their relatively low vulnerability to climate change, most likely also due to the presence of large urban centres (Juhola et al. 2012).

The strength of statistical associations between adaptive capacity and its component indicators varied as shown by correlation analysis (Table 2). Three factors were most strongly correlated with adaptive capacity, i.e. health (human capital), local committees (social capital) and access to credit (financial capital). These statistically significant correlations are consistent with a few studies from other locations. For instance, Berry et al. (2011) found health as an essential component and contributor to adaptive capacity to climate change and suggested that pre-existing health problems are an important factor to consider when designing adaptation programs and policies. A positive association between access to credit and climate change adaptation strategies has been found in many other previous studies. For instance, Deressa et al. (2009) and Fosu-Mensah et al. (2012) found that access to credit has a positive and significant impact on a farmer's likelihood of using many adaptation strategies in the Nile Basin of Africa and Ghana. Likewise, Gbetibouo (2009) noted that lack of access to credit was cited by farming respondents as the main factor inhibiting adaptation to climate change in South Africa.

Aspects of social capital, particularly bridging social capital (Woolcock and Narayan 2000), were strongly associated with adaptive capacity. Bridging social capital brings together people from diverse social backgrounds through networks and connections to attain common goals (Bhandari and Yasunobu 2009). Local zakat committees, used as a proxy for the existence of social networks, were closely correlated with adaptive capacity for Punjab province. The *zakat funds* (transfer payments managed by the government through local zakat committees) are an instrument to bring social welfare to local communities in Pakistan. Through this scheme, needy and marginalised segments of society are provided with *zakat funds* directly via local committees. Many studies found a positive impact of *zakat funds* through local zakat committees in Pakistan. Azam et al. (2014) found that zakat has a positive impact on the economic development of Pakistan and enhances the welfare of households particularly at the micro-level. In addition, Akram and Afzal (2014) found that there is an inverse relationship between poverty and zakat disbursement as a *social safety net* in Pakistan. It is not surprising then, that this indicator appeared to have particular significance, as it is linked not only to social capital but also to the financial capital of communities.

Perhaps surprisingly, literacy level showed the weakest correlation with adaptive capacity (although still statistically significant). In previous studies, the level of education has been shown to play an important role in reducing vulnerability to climate change by increasing an individual's access to information (Donohue and Biggs 2015). However, a possible explanation for the finding in the case of Punjab province is that most of the farmers are generally either illiterate or have no formal school education. Therefore, the low level of education is not as useful to assess relative differences in a district's capacity to adapt as other indicators of human capital. This finding is supported by Fosu-Mensah et al. (2012) who found similar results for a study in Ghana wherein most farmers also had no formal education.

Although there is extensive interest and the demand to quantitatively model vulnerability, there is far less consensus about the ideal set of methods used for the construction of indices (Tate 2012). For example, Reckien (2018) found differences in indices of social vulnerability to climate change depending on the selection methods of index construction (variable addition versus variable reduction) and on the metrics as input data (area based versus population based).

Reckien (2018) further noted that the reductionist approach appears to lack application potential due to difficulty of interpretation and relation to real-world decision-making, while the additive approach does not distort influences of single factors in the overall index, and seems easier to communicate to stakeholders which increases the application potential. In addition, the weighting and aggregation can be determined in several ways including statistical methods (Wiréhn et al. 2017). This paper attempts to include justification for the methodological steps adopted for the study. Comprehensive comparative analysis of different methods for the indicator-based vulnerability assessments is beyond the scope of this paper. However, recent literature indicates that interactive tools such as geovisualisation environment can be useful in vulnerability assessments enabling the underlying indicators and factors determining vulnerability through personalised assessments (Wiréhn et al. 2017). Geovisualisation tools for vulnerability, e.g. ViewExposed (Opach and Rod 2013) and EXTRA interactive tool (Opach et al. 2020) particularly agricultural vulnerability focused tools, is uncommon, e.g. AgroExplore (Wiréhn et al. 2017). Geovisualisation tools facilitate knowledge acquisition and knowledge construction and can be used for communication to facilitate learning about the complexity of vulnerability (Opach and Rød 2013; Wiréhn et al. 2017). Although, even with a comprehensive understanding of the processes and conditions involved, these are limited in their ability to represent dynamic processes such as vulnerability (Vincent 2004). We recognise that the index constructed in this study, based on an additive model with non-weighted variables, will likely have influenced the assessment of vulnerability (Reckien 2018). However, within the limitations imposed by data availability and quality in a developing world context, and when complemented with district scale qualitative assessments, the complex reality of vulnerability can be conveyed to policymakers.

Variations in the vulnerability of Punjab province indicate the key importance of adaptive capacity in shaping vulnerability to climate change. Support for the significance of adaptive capacity for vulnerability mitigation through adaptation is highlighted in several studies. For instance, Pelling (2010) reports that an increase in adaptive capacity has the relative potential to reduce vulnerability, which has placed the enhancement of adaptive capacity at the centre of adaptation research. Adaptive capacity is conceived as the preconditions to enable adaptation and therefore a precursor of it (Nelson et al. 2007). Adaptive capacity can be assessed through top-down national data and through bottom-up locally acquired data (Brown et al. 2010). However, both approaches have benefits and shortcomings. For instance, assessing adaptive capacity using secondary data sources can be time-consuming and may be useful for broad-scale national comparisons but may overlook regional differences

and local drivers of adaptive capacity (Brown et al. 2010; Smit and Wandel 2006). In contrast, bottom-up approaches can be easy to operationalise and provide much insight into relevant communities but may lack policy application as specific case studies cannot be readily generalised to other locations (Brown et al. 2010). The findings of this study are useful beginning steps and facilitate comparative analysis across regions, but they are simply pointers to the need for deeper community-level engagement to better understand the factors that constrain or enable local adaptation and support place-based action.

Implications for adaptation policy

The demand for vulnerability maps among development agencies and governments in policy contexts is growing (Preston et al. 2011; Sherbinin et al. 2017). Climate change policy documents in Pakistan also indicated the need to focus on building capacity to develop maps to identify vulnerable and sensitive areas. However, Preston et al. (2011) noted that mapping in isolation of other dimensions of knowledge (e.g. local tacit knowledge of climate impacts) may lead to over-confidence in a decision-making process under the view that once maps are available, ample information is on hand for effective decision-making. In general, and within a developing country context, there is usually a tendency in government departments to see the maps as the end of knowledge gathering. However, by reframing mapping as the start of knowledge gathering, vulnerability maps can be used for a variety of benefits. For example, maps support adaptation planning (Sherbinin et al. 2017), help spatial planning and can potentially assist with risk or disaster management (Preston et al. 2011). Furthermore, they can act as an instrument of knowledge management (Sherbinin et al. 2017), help identify cross-dependency of services to co-located infrastructure (Inanloo et al. 2016) and aid in the identification of vulnerable areas for prioritisation of action (Preston et al. 2011). Therefore, policy actors can utilise vulnerability maps as a starting point for focusing more detailed sector-based local assessments and that encompass bottom-up information to inform adaptation policy development that accounts for the needs of local communities, ensuring that policy incorporates representational, procedural and distributive justice (Thomas and Twyman 2005; Paavola and Adger 2006; Popke et al. 2016). For this research, vulnerability maps were utilised for the identification of potentially vulnerable areas in Punjab with the aim of using these to target key districts for bottom-up qualitative engagement to better understand how vulnerability assessment can support local adaptation to climate change.

The policy on adaptation in Pakistan reflects the current concentration on broad-scale top-down action embedded in National Adaptation Plans. For instance, The National

Climate Change Policy (NCCP 2012) was developed to direct Pakistan towards resilient climate development. The document provides broad policy measures for both climate change mitigation and adaptation for key sectors including agriculture, health, energy and industries. This national-scale policy document within the adaptation domain indicates general policy measures for the agriculture and live-stock sector under sub-areas of technology, research and risk management. Likewise, 'Vision 2030' prepared by the Planning Commission of Pakistan is also a broad national planning document for the country that emphasises the imperative to prepare to adapt to the coming climate changes and mitigate their negative impacts (PC 2007). On a provincial scale, The Government of Punjab developed a draft Punjab Climate Change Policy (PCCP) which also briefly indicates general mitigation and adaptation policy measures for sectors of Punjab similar to the NCCP (PEPD 2021). However, these high-level policy documents do not provide specific climate change adaptation plans for sensitive or exposed areas of Punjab. As vulnerability, its components and contributing factors vary spatially, one single policy for the whole Punjab is unlikely to address the needs of all regions. This emphasises the vital importance of local biophysical and socio-economic context to formulate adaptation policy. There is often a tendency among national policymakers to emphasise exposure and sensitivity over adaptive capacity in assessing vulnerability and select adaptation strategies based on cost-effectiveness and synergies with existing development and environmental policies (Holler et al. 2020). However, bearing in mind the metaphor of the wounded soldier (O'Brien et al. 2007; Schipper and Burton 2009) (i.e. prior damage limits the capacity to respond to stress) underlying aspects of social vulnerability must be addressed (Ford et al. 2010; Mikulewicz 2018; Williamson et al. 2012).

The issues discussed above point to the need to mainstream adaptation into other policy silos as emphasised by several researchers. Huq and Reid (2004) suggest that successful adaptation to climate change requires the incorporation of potential climate impacts into ongoing strategies and plans. Likewise, Pouliotte et al. (2009) note that climate change adaptation should be integrated into current development priorities. Also, Wise et al. (2014) and Burnham and Ma (2016) suggest that meeting the objectives of human development and climate change adaptation can be accomplished only if they are undertaken in an integrated way. This evidence supports the need for mainstreaming adaptation into other policy processes involving the Punjab province. Therefore, while shaping the Punjab provincial development policies, priority needs to be given to building the adaptive capacity of the least developed and potentially vulnerable areas to climate change such as Southern and Northern Punjab vulnerable districts.

There is scope for local policy actors to have a greater influence on building adaptive capacities particularly in relation to social and human capital in Punjab's vulnerable regions. For instance, social capital can be enhanced through deliberate and relatively low-cost policy interventions (Shrestha et al. 2015) such as support for strengthening local social networks. These types of interventions can allow for knowledge exchange about local needs and facilitate cooperation on adaptation (Bhandari and Yasunobu 2009; Shrestha et al. 2015). Furthermore, social capital facilitates mobilising of community resources for collective action (Bhandari and Yasunobu 2009). Local policy interventions for vulnerable regions of Punjab could begin by targeting capacity-building activities to the key indicators of human and social capital identified in this analysis (Table 2).

Conclusion

This study presents the spatial variations of agricultural vulnerability to climate change at the district level for Punjab province. The relative differences indicate the significance of adaptive capacity in mediating respective vulnerabilities of Punjab districts. Findings suggest the need for policy to focus on building adaptive capacity for vulnerable regions of Punjab province and that a single adaptation policy that fails to account for variations in the causes of vulnerability at local to district scale is unlikely to be effective for the whole Punjab province. The use of a livelihoods approach and statistical associations that recognised the importance of human, financial and social capital as part of the enabling environment for adaptation revealed the factors that contour adaptive capacity and that may be influenced by effective government policies. A policy focus on socio-economic aspects that accounts for place-based biophysical features also points to the need to integrate climate change policies with other general economic and social development policies in Punjab with emphasis on local scale information to inform top-down policy initiatives.

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