Selection of Resilient Crop Species for Cultivation Under Projected Climate Change

Deepa Shree Rawal

Abstract Plant species response to projected climate change would be diverse and dependent on species site specific climate. Therefore, information on species site specific response will be required to build regional species specific adaptation plan. For this identification and implementation of tools and techniques that can predict plant responses to projected climate change would be crucial. There are various methods that can be employed to model species response and mechanistic model is one of the reliable models that can predict the impact. Mechanistic model Tree and Climate Assessment- Germination and Establishment Model (TACA-GEM) has largely been used to predict the climate change impact on wild and agricultural species by identifying resilient species for plantation and cultivation under projected change. TACA-GEM was utilized to predict the impact of climate change on agricultural species in three ecological zones representing eastern mountain, hilly and tropical (Terai) regions considering eight cereals and lentil species in Nepal. Species physiological and phenological parameters with germination experimental data were used to calibrate the model to a range of climate change scenarios by the 2050s. The findings indicate that rainfall is one of the primary factors influencing species germination probability and timing. Moderate rainfall with warm climate projected benefitted germination in tropical site (Saptari) while higher rainfall and colder climate projected was adverse to the germination of most of the species in Bhojpur. The germination probability displayed by wheat and chickpea suggests that these species are the most resilient to projected climatic conditions by the 2050s across all the sites. The study successfully demonstrated site specific species vulnerability to a range of climate conditions. Thus, similar research activity can be employed in different land types to identify resilient crop species for future cultivation.

Keywords Environment · Influence · Agricultural crops · Response · Modeling · Vulnerability

D. S. Rawal (✉)
Nepal Academy of Science and Technology, P. O. Box 3323, Khumaltar, Lalitpur, Nepal
e-mail: deepa.rawal@nast.gov.np

X. Poshiwa and G. Ravindra Chary (eds.), *Climate Change Adaptations in Dryland Agriculture in Semi-Arid Areas*, https://doi.org/10.1007/978-981-16-7861-5_8

Introduction

Global temperature is expected to rise 1.1–2.6 °C by the 2100s, and this may likely change the natural biological systems of the World (IPCC 2013). Climate change will alter the temperature, rainfall, radiation and humidity (Olesen and Bindi 2002), consequently changing the physiological and phenology of species (Hughes 2000). Phenological change is the change in the timing of developmental phases of species like seeding/sowing, germination, budding, leafing, stem growth, flowering/fruiting, seed maturing, senescence and harvesting. Therefore, changes in physiological and phenological events in agricultural plants could alter yield and can have greater economic impact (Chmielewski et al. 2004). Information on crop-weather relationships help farmers in decision making and in building strong adaptation strategies (Chmielewski 2013).

There is a growing trend of using phenological response for climate change assessment studies (Chmielewski et al. 2004) that would provide adaptation guidance aiding in the selection of resilient species for future cultivation. Phenological study can help in identifying the optimal cropping area, species and varieties for plantation in changed climate conditions (Chmielewski 2013) that can help in building regional adaptation plans. However, for this species response, modeling is required for the assessment of species resilience to climate change. There are various methods that can be adopted to model the response and mechanistic models have been highly used for the prediction of climate change impact. Phenological models are largely used to study the impact of climate change on natural, managed ecosystems (Chmielewski 2013) and agricultural lands (BC and Rawal 2017). Plants have a definite temperature requirement 'heat sum' before they attain certain phenological stages (Rajput et al. 1987; Sikder 2009). Generally, for field crops Growing Degree Day (GDD) or Heat Sum Models (HSM) are used to calculate the timing of the consecutive phenological stages (Chmielewski 2013). Mechanistic models TACA (Nitschke and Hickey 2007; Nitschke and Innes 2008; Nitschke et al. 2012) and TACA-GEM (Mok et al. 2012; Rawal and Bharati 2015; BC and Rawal 2017) were used to assess the vulnerability of wild and agricultural plant species to climate change. This model primarily utilizes species physiological and phenological parameters to show germination probability, timing shift, and seedling establishment under projected climate conditions, further aiding in identifying resilient species and implement adaptation measures (Rawal et al. 2015; Rawal and Bharati 2015; BC and Rawal 2017).

Effect of climate change is evident in Nepal and may adversely affect various sectors like forestry, agriculture, livelihoods and many other resources affecting the country's economy (Alamgir et al. 2014). National Adaptation Program of Action (NAPA) shows that Nepal is extremely vulnerable to climate change impacts because its economy heavily depends on natural resources, particularly water, soils, and forests (MOE 2010). Nepal has diverse agricultural zones like plains (Terai), hills, mid hills, high hills and mountains and cropping pattern varies across agricultural zones (Malla 2008). Climate change leading to warmer temperature coupled with rainfall decline is the key determinant that alters the timing of phenological events

(Wheeler et al. 1996; Chakrabart et al. 2010; Amgain 2011a, b) that may negatively affect the yield of rice, maize and wheat (Wheeler et al. 1996; Tao et al. 2006; Lobell and Field 2007; Subash et al. 2011). Increase in temperature can cause more damage to the agricultural sector of the tropical 'Terai' region of Nepal. For example, temperature rise of 4 °C reduced rice and wheat production in the Terai region even as production in the hills and mountains rose, while for maize, production declined in the Terai and hills but increased across the mountains (Malla 2008). Hence, climate change and its effects on crops are of particular concern for the World especially in the arid regions.

Climate change induced production decline has led farmers to seek adaptation measures such as changing the agricultural calendar and cropping patterns (Karn 2014). Climate change can influence the choice of crop species, as poorly adapted species can show higher fluctuation and declinein yield even under a small change in the growing season length (Chmielewski 2013). Temperature rise and changed rainfall pattern can alter present soil condition and evaporation (Fennessey 1994; Falloon and Betts 2010) consequently shifting the timing of germination, growth, flowering and fruiting of crop species affecting the yield and the economy. In such situation, vulnerability identification and risk assessment would be critical for better management of agriculture (Reilly and Schimmelpfennig 1999; IPCC 2014). Furthermore, understanding climate variability, its effect on individual crop species and their response can provide valuable information and guidelines for farmers and decision makers.

Therefore, a key challenge ahead is to identify a suitable resilient species and varieties for future plantation in a particular region. Plant species show diverse response to projected climate change that is dependent on individual species site specific climate. Thus, information on species site specific response will be required to build species specific regional adaptation plans. For this identification and implementation of tools and techniques that can predict plant responses to projected climate change would be crucial.

Modeling tools and techniques are largely been implemented to assess species response to climate change. TACA-GEM has been widely used to predict impact on species abundance under projected climate change. This model can be implemented to predict site specific species response that can help in building regional adaptation plans and has been implemented in Nepal to identify site specific species response to climate change scenarios by the year 2050 for wild and agricultural species (Rawal and Bharati 2015; BC and Rawal 2017). This paper basically relates a novel technique adopted in case of Nepal by Rawal and Bharati (2015) which could largely be employed as an innovative approach for the identification of resilient crop species to projected climate change in different regions across the world.

Materials and Methods

Site and Species Selection

Three districts Sankhuwasabha, Bhojpur and Saptari districts representing three ecological zones hill, mountainous and plain (Terai) of the Koshi river basin in Nepal that has been characterized with high climatic and geographical variability (Sharma et al. 2000; Bharati et al. 2014) was selected for the study. This study was conducted by International Water Management Institute (IWMI) under the Koshi Basin Programme, led by the International Centre for Integrated Mountain Development (ICIMOD), that was supported by the Australian Government through the Sustainable Development Investment Portfolio for South Asia.

Eight species of cereal and lentil viz. *Oryza sativa* L. (two varieties), *Triticumaestivum* L., *Zea mays* L., *Paspalumscorbiculatum* L. and *Vignamungo* (L.) Hepper, *Glycine max* (L.) Merr., *Cajanuscajan* (L.) Millsp., *Cicerarietinum* L. (see Appendix 1 for species details) were selected for the study. These species were selected based on the estimated area of cultivation and amount of production in each district (Central Bureau of Statistics 2013). All the selected species are cultivated across three sites except pigeon pea and chickpea, which are only cultivated in Sankhuwasabha and Bhojpur.

Germination Experiment and Statistical Analysis

Seeds used for the germination experiment were mainly accessed from the seed supplier companies that supply seeds to the farmers and some of the seeds were directly accessed from the local farmers (see Appendix 1 for seed source and varieties). Seed germination experiment was conducted at the Seed Science and Technology Division of National Agricultural Research Centre (NARC), Khumaltar, Lalitpur, Nepal in a randomized factorial design in controlled seed germinator chambers following the guidelines of the International Seed Testing Association (ISTA 2011). Sample consisted of four replicates of 100 seeds for each species. Seeds of *Oryza sativa*, *Zea mays*, *Paspalum scorbiculatum*, *Vigna mungo*, *Glycine max*, *Cajanus cajan* and *Triticum aestivum, Cicer arietinum* were germinated at the average temperature of 25 °C and 20 °C, respectively, under dark conditions. All the species were germinated between the papers (A grade germination paper), and *Paspalum scorbiculatum* was germinated in petri dish lined with filter paper (Whatman 150 mm). Moisture was maintained by adding distilled water every day (ISTA 2011). Seeds were carefully observed for epicotyl hook emergence for each day. Base temperatures used for calculating Growing Degree Days (GDD, Shahba and Qian 2008) are provided in Table 1.

Table 1 Species specific germination parameters and climatic origin taken for the calibration of TACA-GEM model

Parameter	Millet	Rice 4	Rice 11	Maize	Wheat	Pigeon pea	Chickpea	Soybean	Black gram
Habitat									
Soil texture[a]	SL[a]	C[e]	C[e]	CL[a]	S[k]	L[a]	SL[q]	L[q]	L[q]
Seedfall Julian date (days)	120[a]	180[a]	180[a]	95[h]	120[m]	120–140[o]	150l	150[r]	90–120[l]
Rooting zone depth (m)	0.1[ab]	0.1[ab]	0.1[ab]	0.1[ab]	0.1[ab]	0.1[ab]	0.1[ab]	0.1[abs]	0.1[ab]
Coarse fragment (%)[b]	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Probalistic Germination Functions thresholds of polynomial regression for germination based on GDD									
Minimum GDD threshold (days)	20	30	20	30	30	30	30	30	20
Maximum GDD threshold (days)	180	190	200	140	110	170	170	130	120
Minimum temperature (°C)	20[a]	20[a]	20[a]	18[a]	15[a]	18[a]	15[a]	20[a]	22[a]
Maximum temperature (°C)	35[a]	30[a] or	30[a] or	33[a] or	27 [a] or	38[a]	29[a]	33[a]	35[a]
b0	−0.0705	−0.2284	−0.2708	−0.3903	−0.6028	−0.2156	−0.4103	−0.4369	−0.2169
b1	0.0066	0.0112	0.0117	0.0220	0.0384	0.0243	0.0202	0.0248	0.0149
b2	−5.39E−05	−9.3E−05	9.04E−05	−0.0002	−0.0005	−0.0005	−0.0002	−0.0003	−0.0002
b3	1.1E−07	2.1E−07	1.9E−07	5.9E−07	1.6E−06	3.2E−06	4.3E−07	8.2E−07	5.9E−07
Other germination parameters									
Germination moisture threshold (MPa)	−1.0[c]	−1.0[f]	−1.0[f]	−2.0[j]	−2.3[m]	−1.0[p]	−1.70[j]	−1.0[s]	−2.0[u]
Physiological base temperature (°C)	5.1[d]	8[g]	8[g]	6.1[i]	2[n]	10	5.49[j]	5[t]	8[a]

GDD, growing degree days; [a] www.fao.org, [b] Mok et al. (2012); [c] Kader and Jutzi (2003); [d] Russell and Webb (1976); [e] Anonymous 3 (2005); [f] Chauhan and Johnson (2009); [g] Yoshida (1981); [h] Anonymous 2 (2008); [i] Itabari et al. (1993); [j] Finch-Savage (2005); [k] Anonymous 1 (2008); [l] www.nfsm.gov.in; [n] George (1967); [m] Wuest et al. (1999); [n] Khah et al. (1986); [o] Sheahan (2012); [p]Briede and McKell (1992); [q] Heuzé et al. (2012b, 2013a); [r] Usual Planting and Harvesting Dates (1997); [s] Vieira et al. (2004); [t] Covell et al. (1986); [u] Pratap and Sharma (2010)

To determine the relationship between optimum time and temperature needed for germination, germination percentage was analysed as a dependent variable of GDD accumulation using non-linear polynomial regression analysis (McDonald 2009).

Mechanistic Model and Climatic Parameters

The mechanistic model TACA-GEM (Mok et al. 2012), a modified version of TACA (Nitschke and Hickey 2007; Nitschke and Innes 2008; Nitschke et al. 2012) was used to model the species-specific germination responses to climate variability. Species-specific germination parameter GDD thresholds and GDD functions identified from the germination phenological experimental components were used for TACA-GEM calibration (Table 1). Details of the model can be found in Rawal et al. (2015), Mok et al. (2012) and Nitschke and Innes (2008).

For the simulation of past climate conditions (PCC), climate inputs from the ten-year reference period was inputted to TACA-GEM. The climate data include the minimum and maximum temperature (T_{min} and T_{max}), rainfall (R_{mean}) and solar radiation (SR) on a daily time step (*source:* Department of Hydrology and Meteorology, Nepal). The climatic data, climatic points and the years used for each site are provided in Appendix 2. For the site Bhojpur, the R_{mean} values were considered from the climate station 1325 (Dingla, Bhojpur). The temperature data representing Bhojpur (station 1324, Bhojpur, Bhojpur) has a large number of missing T_{min}, T_{max} and R_{mean} data, and climate station 1325 (Dingla, Bhojpur) lacks temperature data. Significant higher correlation exists between the T_{max} ($r \leq 0.87$, $P < 0.0001$) and T_{min} ($r \leq 0.91$; $P < 0.0001$) between the climatic stations 1324 (Bhojpur, Bhojpur) and 1303 (Chainpur, Eastern Sankhuwasabha). Hence, the climate variables T_{min}, T_{max} of the station 1303 (Chainpur, Eastern Sankhuwasabha) has been used to represent the temperature of Bhojpur. Where the missing values exist, the monthly mean of the climatic variables T_{min}/T_{max}/R_{mean}/SR were added. When monthly SR values were missing, the monthly mean of previous or subsequent year was used for the interpolation.

The projected climate model simulations in the Fifth Assessment Report of the IPCC (2014) are based on the Representative Concentration Pathways (RCPs, Moss et al. 2010). Four projected climatic conditions—wet-warm (CanESM2-r4i1p1), wet-cold (CCSM4-r5i1p1), dry-cold (GISS-E2-R-r4i1p1) and dry-warm (IPSL-CM5A-LR-r4i1p1)—that represent 'RCP 45' (Immerzeel and Lutz 2012) were considered for TACA-GEM model simulation. Monthly delta change approach (in detail, Immerzeel and Lutz 2012) has been used to build these four scenarios, which project the temperature and precipitation change by the 2020s–2050s, corresponding three selected sites. The base reference years used to make the four climate projections were from the period 1998–2008 for each site. This delta change approach is considered an efficient way to assess climatic changes (Deque 2007; Kay et al. 2008). Based on the present and the four projected climatic conditions, TACA-GEM output provides germination shift in days and germination probability score ranging from 0–1, indicating total failure (0.0) to 100% success (1.0) in germination.

Average of climatic factors (T_{min}, T_{max}, R_{mean}) used to calibrate the TACA-GEM for PCC and the projected climate change conditions by the 2050s (wet-warm, wet-cold, dry-cold, dry-warm) is provided in Table 2. Analysis of variance (ANOVA) of mean annual T_{min}, T_{max} and R_{mean} of PCC and projected climatic conditions (wet-warm, wet-cold, dry-cold, dry-warm) was carried out to show the climatic differences among the sites Sankhuwasabha, Bhojpur and Saptari. Mean annual T_{min}, T_{max} and R_{mean} of PCC and the four projected climatic conditions (wet-warm, wet-cold, dry-cold, dry-warm) differed significantly ($P \leq 0.001$) across the sites. Bhojpur is significantly wetter and Sankhuwasabha significantly drier while rainfall was moderate at Saptari across PCC and projected climatic conditions. Saptari is significantly warmer than the other two sites across all the climatic conditions and temperature conditions are similar between Bhojpur and Sankhuwasabha. T_{max}, T_{min} and R_{mean} are lower under PCC than the four projected climatic conditions across all the sites (Table 2).

Table 2 Average of climatic factors (T_{min}, T_{max}, R_{mean}) used to calibrate the TACA-GEM for PCC and the projected climate change conditions by the 2050s. Climatic means followed by different superscripts indicates significant differences ($P \leq 0.05$) in climatic conditions (PCC, wet-warm, wet-cold, dry-cold, dry-warm) among the sites Sankhuwasabha, Bhojpur and Saptari

Site	T_{min}	T_{max}	R_{mean}
Sankhuwasabha			
PCC	13.0^{a}	24.7^{a}	4.2^{a}
Wet-warm	14.0^{a}	25.7^{a}	5.0^{a}
Wet-cold	13.7^{a}	25.4^{a}	5.0^{a}
Dry-cold	13.7^{a}	25.4^{a}	5.1^{a}
Dry-warm	14.0^{a}	25.6^{a}	4.9^{a}
Bhojpur			
PCC	13.0^{a}	24.7^{a}	6.8^{b}
Wet-warm	14.0^{a}	25.7^{a}	7.8^{b}
Wet-cold	13.7^{a}	25.4^{a}	7.8^{b}
Dry-cold	13.7^{a}	25.4^{a}	7.8^{b}
Dry-warm	14.0^{a}	25.6^{a}	7.5^{b}
Saptari			
PCC	19.3^{b}	32.3^{b}	5.4^{c}
Wet-warm	20.3^{b}	33.2^{b}	6.1^{c}
Wet-cold	20.0^{b}	32.9^{b}	6.0^{c}
Dry-cold	20.0^{b}	32.9^{b}	6.2^{c}
Dry-warm	20.2^{b}	33.1^{b}	5.9^{c}

Results

The model results demonstrate that species germination response was generally influenced by climatic condition of individual site. However, germination probability of wheat and chickpea were similar across all the sites. Species germination probability was higher across all the climatic conditions projected by the 2050s in Saptari. The result also demonstrates that projected climatic condition of Bhojpur was not favorable for most of the species as germination probability declined.

Site specific species response suggests that at Sankhuwasabha all four climatic conditions were favourable for the germination of wheat, chickpea and soybean. However, the projected dry-cold conditions severely affected the germination probability of millet, rice 11, maize, pigeon pea and black gram while rice 4 was affected by wet-warm conditions (Table 3).

The model results suggested that at Bhopur, PCC is generally more beneficial for germination than projected climate conditions for all the species except rice varieties at this site. Among the projected climate conditions, higher rainfall coupled with cold conditions projected were more detrimental to the germination of most of the species. Across the projected climatic conditions wet –warm condition was more favourable for the germination of all species. Under wet-cold and dry-cold conditions the germination decreased across all the species and germination potential of millet, soybean and black gram declined more sharply than for other species (Table 3).

Moderate rainfall and warmer conditions projected in Saptari mostly benefitted species germination across all the projected conditions. However, the germination of two rice varieties declined under the wet-warm conditions indicating germination vulnerability of rice under warmer condition. Although the germination probability under PCC is lower for wheat and chickpea, projected climate conditions benefitted germination (Table 3).

Discussion

Species Vulnerability

Plant species show various degree of regeneration change under climate changed conditions (Rawal et al. 2015). In this study, the germination response displayed by the species under varied climatic conditions helped in determining the species risk to projected climatic conditions. The germination capacity of wheat and chickpea were not much affected by projected climatic conditions thus displayed wider degree of plasticity. Species demonstration of wider regeneration niche than that of the existing one may provide a larger degree of plasticity (Aitken et al. 2008; Cochrane et al. 2011). Such plasticity was not demonstrated by all the species under projected climatic condition by the 2050s which may risk the germination capacity and seedling establishment. This study therefore, suggests that wheat and chickpea demonstrated

Table 3 TACA-GEM model results of germination probability score ($0 - 1$ indicating no to successful germination) for the study species under PCC (past climate condition) and projected climatic conditions wet-warm, wet-cold, dry-cold and dry-warm by the 2050s

	Millet	Rice 4	Rice 11	Maize	Wheat	Pigeon pea	Chickpea	Soybean	Black gram
Germination probability score (std dev.)									
Sankhuwasabha									
PCC	0.62(0.33)	0.77(0.28)	0.52(0.48)	0.96(0.12)	1.00(2.2E−09)	0. 89(0.15)	0.99(5.4E−05)	0.55(0.41)	0.70(0.31)
Wet-warm	0.78(3.3E−03)	0.69(4.0E−03)	0.59(0.004)	0.99(5.2E−05)	1.00(3.9E−10)	0.96(7.0E−04)	0.99(1.1E−07)	0.65(4.0E−03)	0.76(4.0E−03)
Wet-cold	0.80(0.03)	0.92(1.0E−03)	0.81(3.0E−03)	0.99(1.0E−04)	1.00(4.2E−11)	0.97(6.0E−04)	0.99(3.6E−08)	0.70(4.0E−03)	0.78(3.0E−03)
Dry-cold	0.50(3.0E−03)	0.77(3.0E−03)	0.46(5.0E−03)	0.94(1.0E−03)	1.00(3.4E−10)	0.87(2.0E−03)	0.99(1.6E−08)	0.60(5.0E−03)	0.69(4.0E−03)
Dry-warm	0.86(2.0E−03)	0.97(6.0E−04)	0.92(1.4E−03)	0.99(1.7E−05)	1.00(2.4E−12)	0.97(5.0E−04)	0.99(8.1E−08)	0.77(4.0E−03)	0.85(2.0E−03)
Bhojpur									
PCC	0.71(0.22)	0.78(0.34)	0.67(0.44)	0.99(0.02)	1.00(2.0E−07)	0.86(0.13)	0.99(6.0E−04)	0.57(0.39)	0.79(0.20)
Wet-warm	0.70(4.1E−03)	0.81(3.0E−03)	0.72(4.0E−03)	0.95(1.0E−03)	1.00(4.5E−09)	0.83(3.0E−03)	0.99(4.2E−06)	0.57(5.0E−03)	0.68(4.0E−03)
Wet-cold	0.51(5.0E−03)	0.77(3.0E−03)	0.66(4.0E−03)	0.89(2.0E−03)	1.00(7.7E−09)	0.76(3.0E−03)	0.99(8.2E−05)	0.34(4.0E−03)	0.49(5.0E−03)
Dry-cold	0.51(5.0E−03)	0.81(3.0E−03)	0.67(4.0E−03)	0.94(1.0E−03)	1.00(7.2E−10)	0.76(4.0E−03)	0.99(9.1E−07)	0.40(5.0E−03)	0.53(5.0E−03)
Dry-warm	0.61(5.0E−03)	0.77(4.0E−03)	0.65(4.0E−03)	0.89(2.0E−03)	1.00(4.4E−09)	0.78(3.0E−03)	0. 99(6.3E−05)	0.49(5.0E−03)	0.59(5.0E−03)
Saptari									
PCC	1.00(3.3E−07)	0.87(0.17)	0.99(0.00)	1.00(1.7E−09)	0.47(0.44)	0.99(2.9E−06)	0.95(0.06)	0.99(4.5E−05)	0.99(7.7E−05)
Wet-warm	1.00(1.4E−10)	0.74(4.0E−03)	0.69(3.0E−03)	1.00(7.2E−14)	0.99(1.3E−09)	1.00(4.6E−10)	0.99(4.2E−06)	1.00(3.9E−09)	0.99(1.7E−08)
Wet-cold	1.00(6.1E−10)	0.99(4.6E−05)	0.99(9.5E−05)	1.00(1.9E−13)	0.99(8.2E−06)	0.99(1.6E−07)	0.99(5.8E−07)	0.99(2.5E−07)	0.99(5.9E−08)
Dry-cold	0.99(3.7E−08)	0.99(5.2E−05)	0.99(0.0001)	1.00(5.9E−15)	0.99(5.4E−06)	0.99(4.5E−07)	0.99(3.4E−07)	0.99(1.7E−07)	0.99(9.1E−07)
Dry-warm	1.00(1.3E−10)	0.99(5.9E−05)	0.99(6.8E−05)	1.00(3.3E−15)	0.99(8.6E−06)	1.00(6.6E−10)	0.99(1.5E−06)	0.99(5.9E−08)	0.99(2.4E−08)

higher degree of resiliency that can adapt future changes and can be considered as the most suitable species for future plantation across all the sites. Wheat is grown across a wider range of environments and has greater capacity for adaptation (Anonymous 1, 2008) than any other cereal crops. In the case of chickpea, the species is drought tolerant (Heuzé et al. 2013a) and is distributed across a wide climatic range, from arid, semi-arid, tropical and temperate (www.fao.org). However, chickpea is not currently cultivated in hilly areas like Sankhuwasabha and Bhojpur but this study indicates that chickpea may germinate well in hilly areas as well which also explains the resiliency exhibited by chickpea. Additionally, Covell et al. (1986) suggests introducing chickpeas in new areas as the species is capable of germinating over a wider range of temperatures. Moreover, Venkateswarlu and Shanker (2009) also argue that introducing and cultivating resilient species and varieties that are suitable for a new agricultural system is an adaptation technique.

Millet and maize are highly diverse and are found in different climate zones from temperate to tropical (www.fao.org). This study demonstrates that maize and millet can be resilient to projected climate conditions in Saptari, but the declining germination probability exhibited in Bhojpur and under dry-cold conditions in Sankhuwasabha suggests that these species may become vulnerable at these sites. Maize is a species of warm climate and requires adequate moisture, and hence does perform well in semi-arid or wet climate (Purseglove 1972). Meanwhile, millet can thrive in dry conditions but has limited drought tolerance (Heuzé et al. 2012a; www.fao.org). Hence, the response displayed in Saptari indicates that warm and moderate rainfall conditions projected at this site maintained the germination capacity while extremely wet conditions in Bhojpur and extremely dry conditions in Sankhuwasabha posed germination risk for both the species.

In this study, two rice varieties exhibited varied germination response under similar temperature conditions of Bhojpur and Sankhuwasava. Germination capacity and yield of rice is directly linked to the rainfall condition. Rice plants require less water during nursery stage and high rainfall and excess moisture during this stage may result in lower germination and yield (Karn 2014). Under climate changed condition dry-warm conditions are more prevalent at dry sites due to temperature rise (Dixit et al. 2009; Karn 2014) and such conditions were found to be favorable for germination of rice 4 and 11 in Sankhuwasabha and Saptari. Generally, germination potential for rice needs to be 70% (www.fao.org) for quality assurance. Germination potential (<70%) exhibited by rice 11 across all the projected climatic conditions and sites indicates that this rice variety is relatively more vulnerable than rice 4 variety. Therefore, this study recommends extensive investigation of responses within species, i.e., populations/varieties, to identify suitable population/variety for future plantation.

Among the lentil species, high rainfall in Bhojpur was adverse to the germination of soybean, pigeon pea and black gram indicating that these species require moderate rainfall conditions for germination. Soybean, pigeon pea and black gram all these species perform well in warm, moist and well-drained environments (Arora and Mauria1989; Heuzé et al. 2013b) which explains the species germination resiliency under warm and moderate rainfall conditions in Saptari. Moreover, Soybean is a drought-tolerant species suitable for semi-arid areas and can survive dry spells and recover once favorable conditions resume (Heuzé et al. 2012b).

Spatial Vulnerability

This study demonstrated that species germination potential relied on spatial climatic conditions and germination phase is largely controlled by rainfall. Rainfall variation was the key factor that determined the species germination potential. Temperature conditions are similar in Sankhuwasabha and Bhojpur; however, the varied species responses across the site suggest that higher rainfall in Bhojpur lowered germination capacity for most of the species indicating vulnerability to projected climatic change at this site. However, lower projected rainfall benefitted germination in Sankhuwasabha, indicating lower susceptibility of the species to climate change at this site relative to Bhojpur. Optimum temperature and soil water availability are the principal environmental factors that influence seed germination and emergence (Lindstrom et al. 1976; Fyfield and Gregory 1989). This is consistent with our study findings, which indicated that moderate rainfall with warm climatic conditions in Saptari benefited germination indicating resilience to climate change; although wet-warm conditions may adversely affect two rice varieties. However, uncertainties do exist and irrespective of future climate change, our study indicates that germination of the selected crop species may not be vulnerable to climate change in Saptari by the 2050s.

Furthermore, climate change is expected to affect agriculture very differently in different parts of the World (Parry et al. 1999; Vaghefi et al. 2013). Hence, spatial climatic pattern and its impact and adaptation planning at the regional level have become a key issue (Tao et al. 2008). Therefore, this study was an example to show how modeling tools can be implemented to predict species spatial vulnerability to projected climate change that may help in building adaptation plans that can suit a particular region. This type of modeling tools can be utilized in various land types like moist, arid semi-arid etc. as site specific climate scenarios and environmental factors are utilized to calibrate model for the prediction of plant response. Such studies should be promoted and implemented to assess vulnerability and to devise adaptation plans in regional scale.

Conclusion

This study was able to demonstrate that species exhibit unique germination responses, and such divergent responses are likely to be influenced by regional climatic conditions indicating species vulnerability is reliant on spatial climatic condition. The study was successful in providing some primary insights on how projected spatial climatic variability may affect species germination, thus helping to identify species resiliency to climate change. This study was an example to initiate the use of such models for the prediction of species spatial vulnerability and to identify resilient species for cultivation under climate change. Thus such studies may ultimately help to better predict future consequences and help manage and improve agricultural production at the regional level.

Acknowledgements The extended version of this study has been published (Rawal and Bharati 2015) and was conducted under the support of the International Water Management Institute (IWMI) under the Koshi Basin Programme, led by the International Centre for Integrated Mountain Development (ICIMOD), which is supported by the Australian Government through the Sustainable Development Investment Portfolio for South Asia. This research was partially supported by core funds of ICIMOD contributed by the Governments of Afghanistan, Australia, Austria, Bangladesh, Bhutan, China, India, Myanmar, Nepal, Norway, Pakistan, Switzerland, and the United Kingdom.

Appendix 1: Scientific Name, Common Name, Seed Variety and Source of the Selected Species

Species	Common name	Seed varieties and source
Paspalum scorbiculatum	Millet	Personal communication with a farmer from Kavre
Oryza sativa	Rice 4 (Jeeramansuri)	Khumal 4 (Everest seed company, Khumaltar)
Oryza sativa	Rice 11(Taichin)	Khumal 11 (Everest seed company, Khumaltar)
Zea Mays	Maize	CTake 940 (Everest seed company, Khumaltar)
Cajanus cajan	Pigeon pea	Personal communication with a farmer from Koshi basin
Cicer arietinum	Chickpea	Personal communication with a farmer from Sindhuli
Triticum aestivum	Wheat	WK 1204 (ATC scientific seed conservation center, Khumaltar)
Vigna mungo	Black gram	Personal communication with a farmer from Kavre
Glycine max	Soybean	Sathiyakalo (Everest seed company, Khumaltar)

Appendix 2: Station Number, Site Name and Past Years of Climate Data (T_{max}, T_{min}, R_{mean} and Solar Radiation) Accessed for Three Sites

Site	Geographical position	Station name and code used for T_{max}, T_{min}, R_{mean}	Station name and code used for solar radiation	Past years of climate taken for model input
Saptari	26.53° N 86.73°E	1202 (Phatepur)	1206 (Okhaldhunga)	1994, 1997–1999, 2001–2002, 2006–2009
Sankhuwasabha	27.30 °N 87.32 °E	1303 (Chainpur)	1307 (Dhankuta)	1999–2003, 2005–2009
Bhojpur	27.16 °N87.05 °E	1303 (T_{max} and T_{min}, Chainpur) 1325 (R_{mean}, Dingla)	1307 (Dhankuta)	1999–2003, 2005–2009

References

Aitken SN, Yeaman S, Holliday JA, Wang T, Curtis-McLane S (2008) Adaptation, migration or extirpation: climate change outcomes for tree populations. Evol Appl 1:95–111

Alamgir M, Pretzsch J, Turton SM (2014) Climate change effects on community forests: finding through user's lens and local knowledge. Small-Scale For 13:445–460. [CrossRef] 14

Amgain LP (2011a) Accumulated heat unit and phenology of diverse maize varieties as affected by planting dates under Rampur condition Nepal. Agron J Nepal 2:111–120

Amgain LP (2011b) Agro-meteorological indices in relation to phenology of promising rice cultivars in Chitwan Nepal. Nepal Agric Res J 11:52–59

Anonymous 1 (2008) The biology of *Triticumaestivum* L. emThell. (Bread Wheat) Department of Ageing Office of the Gene Technology Regulator, Australian Government, Australia

Anonymous 2 (2008) The biology of *Zea mays* L. ssp*mays*(maize or corn). Department of Ageing Office of the Gene Technology Regulator, Australian Government, Australia

Anonymous 3 (2005) The biology and ecology of rice (*Oryza sativa* L.) in Australia Department of Health and Ageing, The office of the Gene technology and regulator, Australian Government, Australia

Arora RK, Mauria SS (1989) Vignamungo (L.) Hepper. Record from Proseabase. In: van der Maesen LJG, Somaatmadja S (eds) PROSEA (Plant resources of South-East Asia) Foundation.. Bogor, Indonesia

BC S, Rawal DS (2017) Germination phenological response identifies flora risk to climate change. Climate 5:73–84

Bharati L, Gurung P, Jayakody P, Smakhtin V, Bhattarai U (2014) The projected impact of climate change on water availability and development in the Koshi Basin Nepal. MRD 34:118–130

Briede JW, McKell CM (1992) Germination of seven perennial arid land species, subjected to soil moisture stress. J Arid Environ 23:263–70

Central Bureau of Statistics (2013) Statistical year book of Nepal–2013, Government of Nepal, National Planning Commission Secretariat, Kathmandu, Nepal

Chakrabart B, Aggarwal PK, Singh SD, Nagarajan S, Pathak H (2010) Impact of high temperature on pollen germination and spikelet sterility in rice: comparison between basmati and non-basmati varieties. Crop Pasture Sci 61:363–368

Chauhan BS, Johnson DE (2009) Seed germination ecology of jungle rice (*Echinochloacolona*): a major weed of rice. Weed Sci 57:235–240

Chmielewski F-M (2013) Phenology in agriculture and horticulture. In: Schwartz MD (ed) Phenology: an integrative environmental science, 2nd edn. Springer, Dordrecht, pp 539–562

Chmielewski F-M, Müller A, Bruns E (2004) Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961–2000. Agric for Meteorol 121:69–78

Cochrane AM, Daws I, Hay FR (2011) Seed-based approach for identifying flora at risk from climate warming. Austral Ecol 36:923–935

Covell S, Ellis RH, Roberts EH, Summerfield RJ (1986) The influence of temperature on seed germination rate in grain legumes I. A comparison of Chickpea, lentil and soybean and cowpea at constant temperatures. J Exp Bot 37:705–715

Deque M (2007) Frequency of precipitation and temperature extremes over France in an anthropogenic scenario: model results and statistical correction according to observed values. Glob Planet Change 57:16–26

Dixit A, Upadhya M, Dixit K, Pokhrel A, Rai DR (2009) Living with water stress in the hills of the Koshi Basin, Nepal: International Centre for Integrated Mountain Development. Nepal, Kathmandu

Falloon P, Betts R (2010) Climate impacts on European agriculture and water management in the context of adaptation and mitigation–the importance of an integrated approach. Sci Total Environ 408:5667–5687

Fennessey NM, Kirshen PH (1994) Evaporation and evapo-transpiration under climate change in New England. J Water Resour Plan Manag 120:48–69

Finch-Savage WE, Rowse HR, Dent KC (2005) Development of combined imbibition and hydrothermal threshold models to simulate maize (*Zea mays*) and chickpea (*Cicerarietinum*) seed germination in variable environments. New Phytol 165:825–838

Fyfield TP, Gregory PJ (1989) Effects of temperature and water on germination, radical elongation and emergence of mungbean. J Exp Bot 40:667–678

George DW (1967) High temperature seed dormancy in wheat (*Triticumaestivum* L.). Crop Sci 7:249–253

Heuzé V, Tran G, Giger-Reverdin S (2012a) Scrobic *(Paspalumscrobiculatum)* forage and grain. Feedipedia.org. A program by INRA, CIRAD, AFZ and FAO, www.feedipedia.org. Accessed Oct 2014

Heuzé V, Tran G, Giger-Reverdin S, Lebas F (2012b) Perennial soybean *(Neonotoniawightii)*. Feedipedia.org. A program by INRA, CIRAD, AFZ and FAO, www.feedipedia.org. Accessed Oct 2014

Heuzé V, Tran G, Bastianelli D, Boudon A, Lebas F (2013a) Chickpea *(Cicerarietinum)*. Feedipedia.org. A program by INRA, CIRAD, AFZ and FAO, www.feedipedia.org. Accessed Oct 2014

Heuzé V, Tran G, Boval M (2013b) Black gram *(Vignamungo)*. Feedipedia.org. A program by INRA, CIRAD, AFZ and FAO, www.feedipedia.org. Accessed Oct 2014

Hughes L (2000) Biological consequences of global warming: is the signal already apparent? Trends Ecol Evol 15:56–61

Immerzeel WW, Lutz AF (2012) Manual to generate downscaled climate change scenarios for the downstream basins of the HICAP project. International Centre for Integrated Mountain Development (ICIMOD), Wageningen, the Netherland

IPCC (Intergovernmental Panel on Climate Change) (2013) Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013 The physical science basis: contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

IPCC (Intergovernmental Panel on Climate Change) 2014. Summary for policymakers. In:. Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, White LL (eds) Climate change 2014: impacts, adaptation, and vulnerability. part a: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change, Cambridge University Press, Cambridge, United Kingdom and NewYork, NY, USA

ISTA (2011) International Seed Testing Association, Zürichster, 50, CH-8303 Bassersdorf, Switzerland, ISBN–13978-3-906549-63-7

Itabari JK, Gregory PJ, Jones RK (1993) Effects of temperature, soil-water status and depth of planting on germination and emergence of maize (Zea mays) adapted to semiarid eastern Kenya. Exp Agric 29:351–364

Kader MA, Jutzi SC (2003) Hydrothermal variations and physio-osmotic conditioning effects on five African millet varieties during short term substrate desiccation. J Agric Rural Dev Tropics 104:41–49

Karn PK (2014) The impact of climate change on rice production in Nepal. SANDEE Working Papers, South Asian Network for Development and Environmental Economics (SANDEE), Kathmandu, Nepal

Kay AL, Davies HN, Bell VA, Jones RG (2008) Comparison of uncertainty sources for climate change impacts: flood frequency in England. Clim Change 92:41–63

Khah EH, Ellis RH, Robertsn EH (1986) Effects of laboratory germination, soil temperature andmoisture content on the emergence of spring wheat. J Agric Sci Cambridge 107:431–438

Lindstrom MJ, Papendick RI, Koehler FE (1976) A model to predict winter wheat emergence as affected by soil temperature, water potential, and depth of planting. Agron J 68:137–140

Lobell DB, Field CB (2007) Global scale climate-crop yield relationships and the impacts of recent warming. Environ Res Lett 2:1–7

Malla G (2008) Climate change and its impact on Nepalese Agriculture. J Agric Environ 9:62–71

McDonald JH (2009) Handbook of biological statistics. Sparky House Publishing, Baltimore, Maryland

MOE (Ministry of Environment) (2010) National adaptation program of action to climate change. Ministry of Environment: Kathmandu, Nepal

Mok H-F, Arndt SK, Nitschke CR (2012) Modelling the potential impact of climate variability and change on species regeneration potential in the temperate forests of south-eastern Australia. Glob Change Biol 18:1053–1072

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Ross SK, van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomas AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747–756

Nitschke CR, Innes JL (2008) A tree and climate assessment tool for modeling ecosystem response to climate change. Ecol Model 210:263–277

Nitschke CR, Amoroso M, Coates KD, Astrup R (2012) The influence of climate change, site type and disturbance on stand dynamics in northwest British Columbia, Canada. Ecosphere 3:1–21

Nitschke CR, Hickey GM (2007) Assessing the vulnerability of Victoria's Central Highlands forests to climate change. Technical report, Department of Sustainability and Environment, Melbourne, Victoria

Olesen JE, Bindi M (2002) Consequences of climate change for European agricultural productivity, land use and policy. Eur J Agron 16:239–262

Parry ML, Fischer C, Livermore M, Rosenzweig C, Iglesias A (1999) Climate change and world food security: a new assessment. Glob Environ Chang 9:S51–S67

Pratap V, Sharma YK (2010) Impact of osmotic stress on seed germination and seedling growth in black gram (*Phaseolusmungo*). J Environ Biol 31:721–726

Purseglove JW (1972) Tropical crops: monocotyledons. Longman Scientific and Technical New York

Rajput RJ, Deshmukh MR, Pardakar VK (1987) Accumulated heat units and phenology relationships in wheat as influenced by planting dates under late sown conditions. J Agron Crop Sci 159:343–348

Rawal DS, Bharati L (2015) Identification of crop species vulnerable to projected climate change in three agro-ecological zones of Koshi river basin Nepal. J Hill Agric 6:234–244

Rawal DS, Kasel S, Keatley MR, Nitschke CR (2015) Environmental effects on germination phenology of co-occurring eucalypts: implications for regeneration under climate change. Int J Biometeorol 59:1237–1252

Reilly J, Schimmelpfennig D (1999) Agricultural impact assessment, vulnerability, and the scope for adaptation. Clim Change 43:745–788

Russell JS, Webb HR (1976) 'Climatic range of grasses and legumes used in pastures', result of a survey conducted at the 11th International Grassland Congress. J Aust Inst Agric Sci 42:156–163

Shahba MA, Qian YL (2008) Effect of seedling date, seeding rate and seeding treatment on saltgrass seed germination and establishment. Crop Sci 48:2453–2458

Sharma KP, Moore B, Vorosmarty CJ (2000) Anthropogenic, climatic, and hydrologic trends in the Koshi basin, Himalaya. Clim Change 47:141–165

Sheahan CM (2012) Plant guide for pigeonpea (*Cajanuscajan)* USDA-Natural Resources Conservation Service, Cape May Plant Materials Center. Cape May, NJ

Sikder S (2009) Accumulated heat unit and phenology of wheat cultivars as influenced by late sowing heat stress condition. J Agric Rural Dev 7:57–64

Subash N, Singh SS, Priya N (2011) Extreme rainfall indices and its impact on rice productivity—cases study over sub-humid climatic environment. Agric Water Manag 98:1373–1387

Tao F, Yokozawa M, Xu Y, Hayashi Y, Zhang Z (2006) Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agric for Meteorol 138:82–92

Tao F, Yokozawa M, Liu J, Zhang Z (2008) Climate–crop yield relationships at provincial scales in China and the impacts of recent climate trends. Climate Res 38:83–94

Usual Planting and Harvesting Dates for U.S. Field Crops December, 1997. National Agricultural Statistics Service (NASS), United States Department of Agriculture, Agricultural Handbook Number 628

Vaghefi N, Shansudin MN, Radam A, Rahim KA (2013) Modelling the impact of climate change on rice production: an overview. J Appl Sci 13:5649–5660

Venkateswarlu B, Shanker AK (2009) Climate change and agriculture: adaptation and mitigation strategies. Indian J Agron 54:226–230

Vieira RD, Neto AS, de Bittencourt SRM, Panobianco M (2004) Electrical conductivity of the seed soaking solution and soybean seedling emergence. Sci Agricola 61:164–168

Wheeler TR, Batts GR, Ellis RH, Hadley P, Morison JIL (1996) Growth and yield of winter wheat (Triticumaestivum) crops in response to CO_2 and temperature. J Agric Sci 127:37–48

Wuest SB, Albrecht SL, Skirvin KW (1999) Germination: Vapor transport vs. seed–soil contact in wheat germination. Agron J 91:783–787

www.fao.org. Accessed Oct 2014

www.nfsm.gov.in. Accessed Sept 2014

Yoshida S (1981) Fundamentals of rice crop science. InternationalRice Institute Press, LosBaños, Philippines