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Future agricultural conditions in the Nepal Himalaya - A fuzzy logic approach using high resolution climate scenarios

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Abstract
Until the end of the 21st century, ongoing climate change is expected to trigger major changes in site conditions and vertical species distributions in high mountain regions such as the Himalaya. Altitudinal ranges of species used as staple crops in Himalayan agriculture and currently suitable cultivation areas will be affected as well. Changing climatic variables such as temperature and precipitation will modify agricultural land-use options, and assessments of future crop growth conditions are in high demand. This GIS-based approach utilizes high resolution climate data of the present and two future scenarios and relates them to bioclimatic requirements of the five most important crops grown in Nepal: rice, maize, wheat, finger millet and potato. It takes into account soil pH as a basic constraint for the individual crop. The three factors temperature, precipitation, and soil pH are then combined using a fuzzy logic algorithm. The assessment visualizes the expected shifts in suitable cultivation zones for the individual crops. The results show that wheat is likely to experience the most severe loss of crop suitability until the end of the 21st century, while the cultivation of rice is likely to benefit.

Zusammenfassung

Bis zum Ende des 21. Jahrhunderts wird erwartet, dass der Klimawandel substanzielle Auswirkungen auf Standortbedingungen und vertikale Artenverbreitung in Hochgebirgen wie dem Himalaya hat. Auch die wichtigsten Nutzpflanzen der Himalaya-Region und ihre gegenwärtig geeigneten Anbaugebiete werden betroffen sein. Die landwirtschaftlichen Nutzungsmöglichkeiten werden durch sich verändernde Klimavariablen wie Temperatur und Niederschlag modifiziert, deshalb sind Einschätzungen der zukünftigen Wachstumsbedingungen für diese Pflanzen gefragt. In dieser GIS-basierten Studie werden hochaufgelöste Klimadaten der Gegenwart sowie zwei Zukunftsszenarien mit den bioklimatischen Bedürfnissen der fünf wichtigsten Nutzpflanzen in Nepal korreliert: Reis, Mais, Weizen, Fingerhirse und Kartoffel. Die Analyse berücksichtigt außerdem den pH-Wert des Bodens als maßgeblichen Standortfaktor für die einzelnen Nutzpflanzen. Die drei Faktoren Temperatur, Niederschlag und pH-Wert des Bodens werden mit Hilfe eines Fuzzy-Logik-Algorithmus kombiniert. Die Ergebnisse visualisieren die erwarteten Verschiebungen der für den Anbau der einzelnen Pflanzen geeigneten Zonen. Für den Anbau von Weizen werden in beiden Zukunftsszenarien bis zum Ende des 21. Jahrhunderts die größten Verluste von

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geeigneten Flächen erwartet. Im Gegensatz dazu ist es wahrscheinlich, dass sich geeignete Anbauflächen für Reis erweitern werden.

Keywords Agriculture, climate change, GIS, Himalaya, land evaluation

1. Introduction

Physical and ecological systems in the Himalaya and accordingly Himalayan agriculture are highly vulnerable to changing climate conditions. For example, food production is directly affected by changing intensity and duration of the monsoon (*Malla* 2009; *Shrestha* et al. 2012; *Telwala* et al. 2013; *Panthi* et al. 2015). Insufficient and erratic rainfall and droughts are major causes of crop losses. Moreover, climate-related hazards such as floods and landslides have often devastating effects on agricultural production. Climate affects food production, access (especially in mountain areas), and livelihoods, in particular in mid- and far western Nepal where lack of irrigation water occasionally leads to land abandonment. Thus, food security is highly sensitive to climate risks in Nepal, considered to be one of the most vulnerable agricultural economies within South Asia (*Chalise* and *Naranpanawa* 2016).

Apart from climate risks, climate warming may also provide better growth conditions in some regions or altitudinal zones, and could lead to diversified land-use systems as well as to shifts of land-use types from lower to higher elevated areas. Vertical distribution ranges of species including those used as staple crops by local farmers are sensitive to climate change impacts and associated changes in site conditions. Thus, areas currently suitable for the cultivation of specific crops may become unsuitable in future. The need of impact identification and adaptation to cope with vulnerabilities is often expressed in the literature (*Malla* 2009; *Sherpa* et al. 2015; *Chalise* and *Naranpanawa* 2016). In order to formulate adaptation strategies, it is indispensable to analyse the impacts of climate variations on future crop performance in greater detail.

Serious climate change effects on agricultural land use are expected given the above-average warming rates in the Himalayan mountain system. These warming trends distinctly exceed the global mean trend (*IPCC* 2013). Precipitation trends in the Himalaya, characterized by pronounced spatial and seasonal variations and rather decreasing than increasing precipitation, in particular during summer (*Schickhoff* et al. 2016), also affect agricultural production. A station-based analysis of *Hasson* et al. (2016) found widespread drying tendencies over most of High Asia in recent decades, with a significant precipitation decrease over the northwestern Hindu Kush Himalayan region in March.

In Nepal, the average annual mean temperature trend is 0.6 °C per decade for the period from 1977 to 2000 (*Shrestha* and *Aryal* 2011), with a mean maximum temperature trend in winter (December to February) of 0.9 °C per decade for the Himalayan region, and 1.2 °C per decade for the Trans-Himalayan region (*Schickhoff* et al. 2016). This leads to an extended growing season by 4.7 days at average during a 25-year period, with seasonal and regional variations (*Shrestha* et al. 2012). The rate of warming is amplified with elevation, and the increase of winter temperature trends is highest compared to other seasons and the annual mean (*Schickhoff* et al. 2016; *Hasson* et al. 2016). Spatial variation of temperature changes follows the country's altitudinal gradient. Minor temperature increase has been observed at the low elevated moist plains of the Terai region and pronounced warming at middle and high elevations (*Singh* et al. 2011).

Annual precipitation data of Nepal (1959-1994) do not show significant long-term trends, but a significant downward trend after 1990 (*Shrestha* et al. 2000). *Duan* et al. (2006) detected a decline of monsoonal precipitation over the twentieth century, and *Wang* et al. (2013) reported an enhanced frequency of winter and pre-monsoon drought events in western Nepal. In spite of recent decreases in monsoonal precipitation, models and scenarios project an increase in total monsoonal rainfall as well as increasing interannual variability and extremes for the coming decades (*Christensen* et al. 2013; *Hijioka* et al. 2014). It is very likely that increased atmospheric moisture content will compensate for a weakening monsoon circulation. Local farmer's perception of climate change more or less corresponds to available station data. Farmers' observations comprise increased temperatures and unpredictable precipitation in Nepal (*Biggs* et al. 2013; *Sherpa* et al. 2015), with increased frequency of heavy and decreased frequency of moderate rainfall events (*Singh* et al. 2011).

To date, detailed effects of climate change on land use in Nepal are still relatively rarely reported (cf. *Kollmair* and *Müller-Böker* 2002; *Manandhar* et al. 2010; *Government of Nepal* 2012; *WFP* 2014; *Chalise et al.* 2015, 2017; *Pandey* and *Bardsley* 2015; *Schmidt-Vogt* and *Miehe* 2015). This paper addresses research deficits regarding regional impacts of climate change on crops and agricultural production in Nepal. It also aims at visualizing the spatial dimension of these impacts by illustrating possible shifts of suitable areas for crop cultivation.

Crop cultivation in the Himalayan mountain system is constrained by complex topography, high relief energy with steep slopes, and the three-dimensional landscape ecological zonation. Climate change may further affect agricultural production by corresponding changes in edaphic and climatic site conditions. Future local/regional temperature ranges potentially exceed the tolerance limits of major crop species. Thus, the guiding question of this paper is: How will climate change affect the agricultural suitability of the most important crops grown in Nepal?

Favourable climatic conditions are important for optimal yields. Relationships between climate variation and crop yields have been investigated by several authors and at different scales (*Malla* 2009; *Bhatt* et al. 2013; *Poudel* and *Kotani* 2012; *Poudel* and *Shaw* 2016). Although negative effects on crop yields due to temperature increase were broadly observed, most studies found heterogeneous impacts depending on altitude and crop species (*Bhatt* et al. 2013; *Poudel* and *Kotani* 2012; *Poudel* and *Shaw* 2016), demanding tailor-made adaptation measures and further research (*Poudel* and *Kotani* 2012).

While the focus of many studies is on a specific region within Nepal, this paper extends the perspective to the entire country using Geographic Information Systems (GIS) to visualize the results in high resolution. Climatic variables such as temperature and precipitation may constrain the ability to maintain and increase agricultural production in countries like Nepal; thus, assessments of future crop growth conditions are in high demand. We apply a GIS-based approach utilizing high resolution climate data of the present and two future scenarios and relating them to the tolerance levels of the five most important crops grown in the region: finger millet, maize, potato, rice and wheat. Our approach also takes the soil pH into account as a basic constraint for the individual crop. The corresponding shifts in crop suitability are assessed for medium-low (RCP4.5) and high (RCP8.5) emission scenarios, which are identical to those used by the IPCC.

2. Study area

Nepal, located in the centre of the Himalayan mountain range between longitudes 80°05'E to 88°10'E and latitudes 26°20'N to 30°25'N, can be broadly separated into three agro-ecological zones (Terai, Middle Mountains, High Mountains), corresponding to major physiographic regions (*Fig. 1*; cf. *Government of Nepal* 2012; *Miehe* 2015). The percentage of arable land decreases from the Terai via Middle to High Mountains (*Government of Nepal* 2012) due to rugged topography at higher elevations. The Terai is by far the most intensely used region for crop cultivation (*Uddin* et al. 2015).

Nepal's climate is monsoonal, with approx. 80 % of the annual precipitation generated during the monsoon season from June to September. The rugged terrain and vast orography of the country cause complex regional and local climatic differences (*Böhner* et al. 2015). Climate patterns in Nepal range from warm and humid, subtropical-tropical conditions in the south to cold, alpine and arctic-like conditions in the north (*Zurick* and *Pacheco* 2006). Hot, wet summers and dry, mild winters characterize the climate of the Terai lowland of Nepal. The Middle Mountains have warm to mild, wet summers, and cool, dry winters. The High Mountain, alpine climate is characterized by cool summers and frosty winters with comparatively low amount of precipitation.

Annual precipitation in Nepal decreases along an east-west gradient with more than 2000 mm in the east and about 1000 mm in western Nepal (*Government of Nepal* 2012). Dry Trans-Himalayan valleys in northwest Nepal may receive less than 300 mm, while precipitation sums of up to 5500 mm were recorded in front of massifs such as the Annapurna Range (*Miehe* et al. 2001). Cultivation of crops and cereals depends strongly on monsoonal precipitation: Irregular monsoon cycles directly affect crop yields, generating food insecurity for the people of Nepal (*Manandhar* 2002; *Government of Nepal* 2012).

Agriculture is the primary occupation (approx. 66 % of population occupied in agriculture in 2011), the backbone of the Nepalese economy (approx. 34 % contribution to GDP in 2012/13), and the major source of livelihood of the people (*Government of Nepal* 2014; *Schmidt-Vogt* and *Miehe* 2015). It is the dominating land use throughout Nepal, about one third of the country's territory is covered by cultivated land (*Uddin* et al. 2015). Mixed farming systems comprising livestock production, crop cultivation and the use of non-timber forest products represent the major land-use practice in Nepal (*Government of Nepal* 2012). Agriculture is closely linked to grasslands and forests, the latter being the natural vegetation in vast areas of Nepal. Both domains provide fodder for animals and products for market-oriented use as well as for own consumption and subsistence (*Schmidt-Vogt* and *Miehe* 2015).

Crop cultivation is constrained by widespread macro- and micronutrient deficiency of the soils in Nepal. Low pH values prevail due to acidic bedrock. Soils in the Terai, developed from alluvial sediments, are among the most fertile in Nepal. However, even there phosphorus deficiency occurs. Complex interactions of physical factors (e.g., steep slopes, intense precipitation) and human impact (e.g., deforestation, intense grazing and crop cultivation) cause soil degradation and erosion (*Carson* 1986; *Bäumler* 2015; *Schwab* et al. 2015).

Cultivation of cereals (rice, wheat, maize) dominates in the Terai and lower ranges of the Middle Mountains. Crop cultivation changes with increasing elevation. Rice is the most common crop in subtropical regions up to approx. 800 m a.s.l., maize and wheat fields become more frequent at higher middle mountain elevations, while barley and potato prevail in the temperate regions above 3000 m (*Schmidt-Vogt* and *Miehe* 2015). In addition to cereal and livestock production, farmers cultivate different vegetables and cash crops for both subsistence and commercial use, in particular in the Terai and the Middle Mountains (*Government of Nepal* 2012).

In terms of cultivated area, the most important cereal crop in Nepal is rice (*Photo 1*), followed by maize, wheat, millet and potato. Potato represents an important staple food in mountain regions (*Tab. 1*; *Government of Nepal* 2014).

The yield (production per area) of maize and wheat increased during the period 2001/02 to 2010/11, while the amount of harvested millet per ha stagnated. During the same period, the yield of rice showed an unstable trend, with a variability of nearly 20 %. These fluctuations are related to interannual variations in precipitation sums, pointing to a high susceptibility to climatic variability (*Regmi* 2007; *Government of Nepal* 2012; *Dahal* et al. 2015).

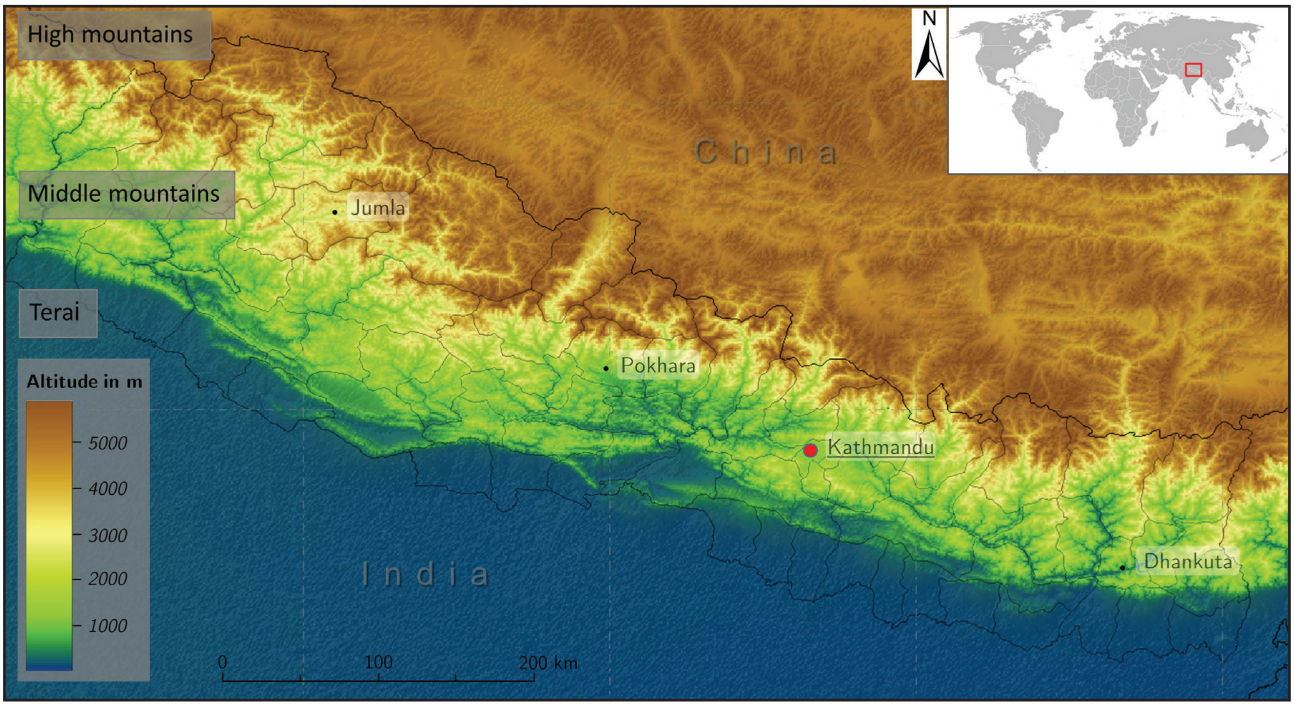

Fig. 1 Map of the study area with an underlying digital elevation model. Kathmandu is marked in red, Terai is coloured in blue, Middle Mountains are coloured in green, and High Mountains in brown. Source: based on physiographic regions in Government of Nepal (2012) and Miehe (2015)

Photo 1 Rice terraces in the lower Marsyangdi Valley, Nepal. Rice is the primary food source for local people in the lower middle mountains and the Terai. Photo credit: U. Schickhoff 09/2013

Table 1 Area, production and yield of major crops in Nepal 2013/14. Source: Government of Nepal (2014: 10, 17)

Crop	Area [km²]	Production [Gt]	Yield [t/ha]
Rice	14,870	5,047	3.394
Maize	9,288	2,283	2.458
Wheat	7,545	1,883	2.496
Millet	2,712	304	1.121
Potato	2,057	2,817	13.695

3. Data and methods

The Himalayan mountain system is a region with poor data availability, partly due to its low accessibility. In particular, information on climate and soil physical and chemical properties is limited. This poses restrictions on conventional land evaluation techniques used in other studies (*FAO* 2007; *Bonfante* and *Bouma* 2015).

The methodical approach used in this analysis expands on a GIS-based approach we applied in an assessment of future agricultural conditions in southwestern Africa (*Weinzierl* and *Heider* 2015). We compare the requirements of the most important crops (see *Table 2* for the major crops in Nepal) with climate data for both the present situation and future scenarios to define suitable areas for each individual crop and visualize expected shifts. The approach was updated here to include soil pH values instead of main soil types. As a representation of present climatic conditions, we utilize information on monthly mean temperature and precipitation sums from the Worldclim (*Hijmans* et al. 2005) dataset. It is available in a spatial resolution of 1 km and covers spline interpolated climate records from 1950 to 2000. In mountainous and poorly sampled areas, the inherent uncertainty is comparatively high. To enable a comparison with crop requirements, the data is aggregated to annual averages/sums.

The future climate scenarios used in this analysis were initially computed by the American National Center for Atmospheric Research (NCAR) with their Community Climate System Model (CCSM4; *Gent* et al. 2011) and use the latest available timeframe, which is the 2080s. Two RCPs (Representative Concentration Pathways) were selected as scenarios of possible future greenhouse gas emissions. RCP4.5 represents a medium-low and RCP8.5 a high scenario, in which the values 4.5 and 8.5 indicate the projected increase in radiative forcing (W/m^2; *Meinshausen* et al. 2011). To enhance the spatial resolution, they were further downscaled to 1 km via a delta method approach (*Ramirez* and *Jarvis* 2008). The climate model scenarios show that in both emission scenarios an increase in temperature is very likely. While the medium-low scenario RCP4.5 assumes an increase of around 2 °C relative to the present state (1950-2000), an increase of around 4 °C is projected in the high emission scenario RCP8.5 for most parts of the study area. The precipitation is likely to increase slightly, especially in central Nepal. For this region, most precipitation increases are projected under RCP8.5. As an additional constraint for plant growth, spatially explicit data of mean soil pH were obtained from *ISRIC* (2013). Soil pH values were determined in water suspension; the data set has a resolution of 1 km (*Hengl* et al. 2014).

Soil pH, mean temperature and annual precipitation requirements for the five most important crops in Nepal, including optimum and absolute ranges (*Table 2*), were obtained from the Ecocrop database (*FAO* 2016). We refrain from including climate change effects on soil pH values in the analysis since a change in soil reaction cannot be accurately predicted. For instance, existing buffering pools in soils which are highly differentiated at regional and local scales determine the extent to what significant increases in rainfall will result in increases in leaching, loss of nutrients, and increasing acidification (*Karmakar* et al. 2016). Absolute precipitation maxima are not included in the analysis since they are considered unrealistic when a minimal human modification (e.g., redirection of surface runoff) can be expected. We do not consider in our analysis any human influence regarding the suitability of areas, for example, by irrigation systems or fertilizer application, i.e. we focus on *natural suitability*. Thus, areas might be illustrated as unsuitable for crop cultivation in which cultivation is actually conducted.

We conducted the spatial analysis in SAGA-GIS (System for Automated Geoscientific Analyses), a cross-platform open source Geographic Information System-software developed by the Departments of Physical Geography in Göttingen and Hamburg (*Conrad* 2007; *Conrad* et al. 2015). To visualize the potential effects of climate change on the cultivation of crops, we applied a fuzzy logic approach. First, we fuzzified the temperature, precipitation, and soil pH datasets according to the optimal and absolute requirements, shown in *Table 2,* to derive the respective suitability in cell values from 0 (not suitable at all) to 1 (very suitable). As the model is a simplification of reality, we assumed a linear relationship between the absolute and optimal values (*Weinzierl* and *Heider* 2015). The model assumes that the soil pH stays constant in time. The three fuzzified datasets were then combined using the 'AND Intersection'-algorithm with the min-operator in the Fuzzy Logic module of SAGA-GIS. This algorithm assigns the lowest cell value from the different inputs. This means that if in one cell cultivation is not possible at all because not all requirements are met, the output will be 0. When two of the factors are optimal, the third factor determines the overall suitability if its value is beyond the optimum range. For example, if the mean temperature is 20 °C, the annual precipitation is 1000 mm, and the soil pH value is 5, the area would not be suitable for the cultivation of finger millet. Precipitation and temperature values are in the optimum range, but the soil pH value is under the absolute minimum and therefore the decisive factor for non-suitability. The result is a spatially explicit dataset showing the overall suitability for each crop. To make future changes better visible, we performed a change detection by subtracting the suitability of the current data (1950-2000) from each scenario (2080-2089).

Table 2 Requirements of the main crops in Nepal. Source: data from FAO (2016)

Plant	absolute min	optimal min	optimal max	absolute max*
Finger Millet (*Eleusine coracana*)				
Mean temperature	8 °C	18 °C	30 °C	35 °C
Annual precipitation	300 mm	500 mm	1100 mm	4300 mm
Soil pH	5.5	6	7	8.2
Maize (*Zea mays*)				
Mean temperature	10 °C	18 °C	33 °C	47 °C
Annual precipitation	400 mm	600 mm	1200 mm	1800 mm
Soil pH	4.5	5	7	8.5
Potato (*Solanum tuberosum*)				
Mean temperature	7 °C	15 °C	25 °C	30 °C
Annual precipitation	250 mm	500 mm	800 mm	2000 mm
Soil pH	4.2	5	6.2	8.5
Rice (*Oryza sativa*)				
Mean temperature	10 °C	20 °C	30 °C	36 °C
Annual precipitation	1000 mm	1500 mm	2000 mm	4000 mm
Soil pH	4.5	5.5	7	9
Wheat (*Triticum aestivum*)				
Mean temperature	5 °C	15 °C	23 °C	27 °C
Annual precipitation	300 mm	750 mm	900 mm	1600 mm
Soil pH	5.5	6	7	8.5

**Absolute maximum values of precipitation are excluded in the analysis*

4. Results

The suitability values for present conditions (*Fig. 2*) range from 0 for not suitable at all (dark red) to 1 for perfectly suitable with all values of temperature, precipitation and soil pH in the optimum range of the crop (dark green). In most areas of the study region, not all requirements are met within the optimum range, thus, the suitability values lie somewhere between 0 and 1. The fuzzy logic approach rather works with rough class memberships than definite ones. For this reason, the differences in suitability can be seen in fine nuances illustrated in a colour range from dark red over yellow to dark green.

The suitability maps for the present state (1950-2000) indicate that the climatic suitability is restricted for the crops in the region. Cold temperatures restrict the suitability at high elevations (*Fig. 2*).

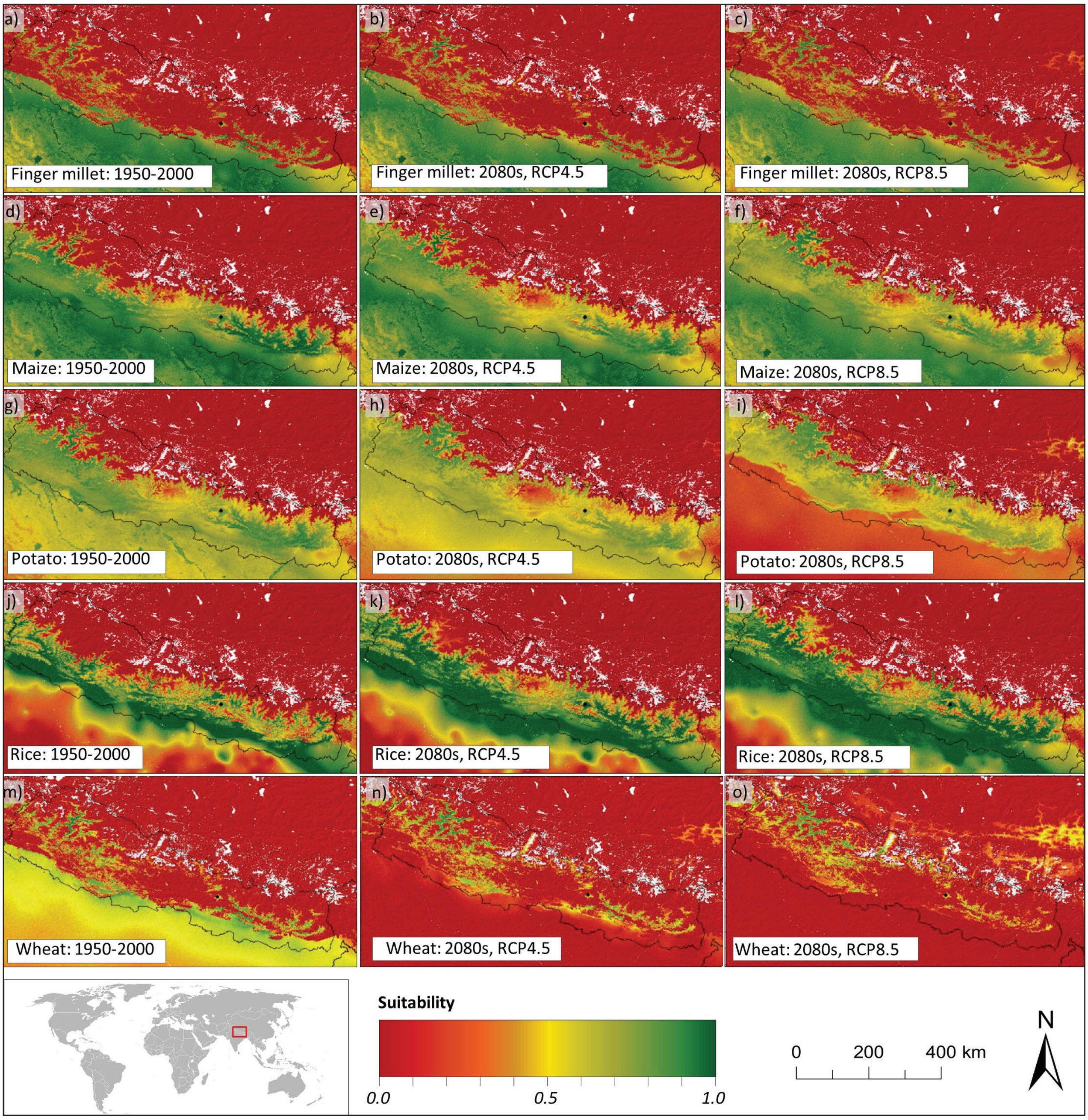

Fig. 2 Natural suitability for the five main crops in Nepal derived from Worldclim data (left column) and two NCAR CCSM4 climate model scenarios (middle and right column). Kathmandu is marked in black. No data regions are shown in white. Source: own elaboration

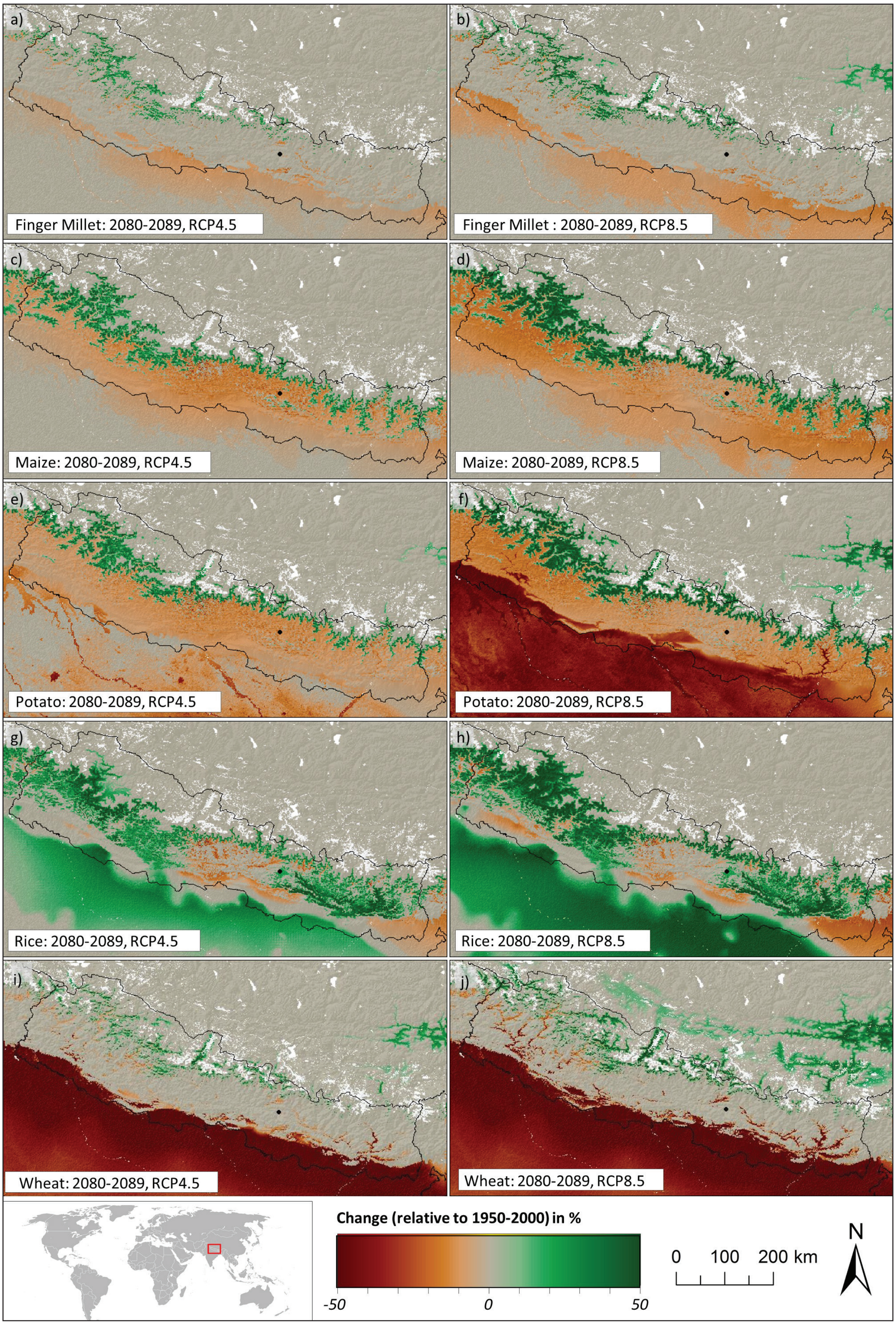

Fig. 3 *Change in natural suitability for the five main crops derived by subtracting the current suitability from that of each climate scenario. Kathmandu is marked in black. No data regions are shown in white. Source: own elaboration*

The suitability of finger millet and wheat in Nepal is limited due to low pH values in the Middle Mountains. Areas of high suitability for finger millet are located mostly in the Terai along the border of Nepal to India. Maize has a very good suitability in most of the study area as long as temperatures are not too low for cultivation. Potato is more adapted to cold temperatures. Hence, it can be cultivated at higher elevations than most of the other crops, even though it is also appropriate in the lowlands. Areas in the northern Gangetic Plain in India tend to be too warm and are situated outside the optimum temperature range, but nevertheless still suitable enough for the cultivation of potato. The suitability for rice is high in the lowlands and the lower Middle Mountains, but limited south of the border to India due to insufficient precipitation and to the north due to cold temperatures. Wheat is, like potato, especially suitable at higher elevations, but restricted in its suitability by high temperatures south of the Nepalese-Indian border. In the north, wheat is limited by cold temperatures, but still suitable in some areas where temperatures are too low for most of the other crops.

Changes in suitability under the medium-low and high emission scenario projected for 2080-2089 relative to 1950 to 2000 are shown in *Figure 3*. The depicted changes range between -50 % (dark red) and +50 % (dark green). The results illustrate that the suitability for the five crops analysed in the study area is likely to change. In both scenarios, all crops are projected to experience an increase in suitability to the north towards higher elevations, to be attributed to higher temperatures. These changes are more moderate in RCP4.5 than in RCP8.5 (see *Fig. 3*).

Whereas positive effects on the suitability at higher altitudes occur, decreases in suitability to the south can be expected. Finger millet as well as maize are projected to be less suitable along the Nepalese-Indian border because projected precipitation may exceed the optimum values for both crops (cf. *Table 2*). Nonetheless, both crops will retain a basic suitability for cultivation in the area. Finger millet is the crop which is projected to experience the smallest changes in suitability. Potato is likely to lose suitability of up to 50 % in RCP8.5 relative to the present state due to temperature increase. While potato has still a moderate suitability from the centre of Nepal southwards under the RCP4.5 scenario, it is classified in RCP8.5 as not very suitable for India and the border region between India and Nepal (*Fig. 2*). Like the other crops, rice is projected to gain suitability due to the temperature increase in the High Mountains, but also due to a projected increase in rainfall in southern Nepal and northern India. The biggest loss of suitable areas is projected for wheat. A negative change of approx. 50 % is projected under both emission scenarios (*Fig. 3*). Due to its preference for cold temperatures (cf. *Table 2*), wheat is likely to be unsuitable in the lowlands in the south of Nepal and in northern India because of the projected temperature increase. Its suitable zone has clearly moved northwards as can be seen in *Figure 2*.

In summary it can be stated that rice is likely to be the crop that benefits most from changing climatic conditions and wheat is projected to lose a considerable part of its suitable area. All crops are likely to experience a better suitability at higher elevations until the end of the 21st century.

5. Discussion

In order to validate our results with regard to areas identified as suitable for crop cultivation under present conditions, comparisons with maps of crop yields of the years 2010/2011, published in the Agriculture Atlas of Nepal (*Government of Nepal* 2012), are appropriate, even though in our analysis no human yield alteration practices are considered (e.g. irrigation, use of fertilizers or pesticides), and only major site factors (temperature, precipitation, soil pH) are included.

The rice production is concentrated in the Terai districts at the border to India. The 20 border districts comprise not more than approx. 23 % of the territory of Nepal, but hold approx. 66 % of Nepal's rice field area, and approx. 70 % of Nepal's rice is produced there (*Government of Nepal* 2012). In line with the crop yield maps, our suitability maps show the Terai lowlands at the border to India to be areas with the highest suitability for rice (cf. *Fig. 2*).

The major areas of maize production are distributed in districts of the lowland and of the Middle Mountains, with some centres such as Bhojpur, Jhapa, Bara, Khotang and Syangja (*Government of Nepal* 2012). The analysis of the suitability for maize corresponds to those areas described by the *Government of Nepal* (2012) as particularly suitable (cf. *Fig. 2*).

Millet is mainly produced in the Middle Mountains and mountain districts of central and east Nepal (*Government of Nepal* 2012). By contrast, our analysis suggests a very low suitability for millet in most parts of the study area due to low soil pH values. Exemptions include the lowlands near the border to India and some areas at higher elevations (cf. *Fig. 2*). The discrepancy between reported areas of millet cultivation and our suitability analysis points to a massive melioration of agricultural lands (see below).

Wheat production in Nepal is conducted in the lowlands and in the Middle Mountains (*Government of Nepal* 2012). The analysis suggests a very low suitability for wheat due to low soil pH values in the Middle Mountains. In the Terai lowlands, the suitability is higher and corresponds to the reported main areas of wheat cultivation. Wheat is projected to lose suitability of approx. 50 % under both emission scenarios in the lowlands of Nepal (cf. *Fig. 3*), which is the main cultivation area and where currently the highest yields in wheat cultivation are reported (*Government of Nepal* 2012).

Potato is produced in largest quantities in the districts of east and central Nepal, covering the entire elevational range from lowland to high mountain districts. In east Nepal, the potato production is concentrated in the lowland districts (*Government of Nepal* 2012). This corresponds to the results of our suitability analysis (cf. *Fig. 2*). A large part of the study area including high elevations is appropriate for potato cultivation. Especially the potato cultivation in eastern Nepal, which is concentrated in the lowlands, will be at risk due to rising temperatures. Under RCP8.5, a negative change of approx. 50 % of suitability is projected in areas, which currently provide highest yields in Nepal.

In general, our results indicate that low temperatures are the limiting factor for crop cultivation at high elevations in the central and northern parts of the study area. The results further suggest that crops can be grown at higher elevations in future as the Nepal Himalaya is subjected to above-average climate warming, in line with other studies on climate change effects on Himalayan farming. Based on a station data-derived elevation-temperature relationship, *Aase* et al. (2017) estimate that a minimum temperature increase of 1 °C allows crops to be grown at 190 m higher elevation, and that a 3 °C increase raises the potential elevation by 560 m, given a constant water availability. In the south, the rising temperature is projected to be a serious limiting factor for the cultivation of potato and wheat.

Our results further indicate that finger millet and maize (as well as rice in the centre and southeast of Nepal) will lose suitability due to an increase in precipitation, which implies values outside the optimum range. Soil pH values below 5.5 are identified by our analysis as a constraint for the cultivation of finger millet and wheat in the Middle Mountains. The limiting effect of the soil pH value for finger millet and wheat is obviously compensated by human melioration of the agricultural environment. Although low pH values are considered a limiting factor for cultivation in the Middle Mountains, cultivation of finger millet and wheat is indeed taking place with relevant harvest yields (*Government of Nepal* 2012). That all crops analysed here are produced in most districts of Nepal's agro-ecological zones in relevant quantities has to be attributed to melioration activities such as liming, N (nitrogen) fertilization, P (phosphorus) and K (potassium) applications and the like.

At a global scale, climatic changes will modify the geography of crop suitability. Addressing the impact of changing temperatures and precipitation and using the Ecocrop dataset in their analysis, *Lane* and *Jarvis* (2007) found a general increase in suitable areas for crop cultivation, while suitable areas for the cultivation of cold weather crops such as wheat are likely to decrease. Our findings for Nepal and North India corroborate this result, especially for wheat and potato.

It is important to point out again that our analysis assumes no human intervention. The absolute maximum values of precipitation for the selected crops are not included in the analysis, because a negative influence on the crops could be easily prevented, for example, by redirecting surface runoff into channels. Additionally, seasonality and extreme temperature values are not yet included. Since the analysis does not consider irrigation or fertilization, areas identified as unsuitable may be actually suitable due to human input. Cultivation practices can have an influence on suitability, because soil is a dynamic system and its properties might change over time (*Bonfante* and *Bouma* 2015). Thus, the results of the presented approach should not be mistaken as an exact representation of actual current and future situations.

It appears likely that the significance of our results could be improved by better data availability. The study area can be considered a poor data region. For instance, a soil pH value of a certain locality might be different from the interpolated value in the database. Medium values in the database for tolerance limits of crop species are another potential source of noise. The tolerance limit of a specific crop might differ in reality, for instance, due to the introduction of new varieties or strains of plants more resistant to changing environmental conditions.

Applying fuzzy logic in SAGA-GIS to quantify and combine different datasets proved to be meaningful in a previous study (*Weinzierl* and *Heider* 2015) and in this one. We transferred the previous approach to another study region, and enhanced it by the use of soil pH values as an additional requirement suggested by the FAO Ecocrop database (*FAO* 2016). We added maps of changing suitability for a more illustrative comparison between different climate scenarios. Scientists increasingly use fuzzy approaches to work with uncertainties, sparse information and class membership, which is rough rather than definite (*Malczewski* 2006; *Chaddad* et al. 2009; *Delgado* et al. 2009; *Keshavarzi* et al. 2010; *Elaalem* et al. 2011, *Elaalem* 2012). Fuzzy logic has also the advantage to require only moderate computing resources. Described by *Zadeh* (2008: 2751) as "precise logic of imprecision", fuzzy logic is able to display continuous transitions found in nature unlike the concrete thresholds known from Boolean mapping methods (*Burrough* 1989; *Baja* 2001; *Delgado* et al. 2009; *Keshavarzi* et al. 2010). It is also recommended for the classification of soil survey data in the revised FAO land evaluation framework (*FAO* 2007). A better picture of reality is gained by the creation of continuous classes and the introduction of terms like 'slightly better' or 'relatively dry' to land evaluation. Using fuzzy logic, spatial trends can be illustrated and interpreted more realistically than with Boolean approaches (*Elaalem* 2012).

In spite of some constraints, we consider this analysis to be a robust approximation of the natural preconditions and their development in future. It represents a land suitability analysis, which contributes a new tool and new findings to the wider framework of land evaluation, linking land suitability concepts to sustainable management of land resources (*FAO* 2007). Recently, an increasing number of studies has been conducted within this framework (*Keshavarzi* et al. 2010; *Elaalem* et al. 2011; *Elaalem* 2012; *Arshad* et al. 2013a,b; *Bonfante* and *Bouma* 2015).

6. Conclusions

Spatially explicit analyses of the future agricultural potential provide a strong foundation for the development of adaptation options in agriculture to climate change. For this case study of Nepal, the correlation of climatic scenarios with data on the requirements of the five most important crops (rice, maize, wheat, finger millet and potato) proved to be adequate and effective. The results suggest that climate change impacts vary significantly between different crops and emission scenarios. However, all crops are projected to gain suitability at high elevations due to increased temperatures. While rice is expected to benefit from climate change due to an increase in precipitation in the southern part of the study area, wheat and potato are likely to lose suitable cultivation areas under warmer conditions in the south.

Despite some uncertainties, this analysis provides robust information to stakeholders and decision-makers on constraints that are likely to affect Nepalese agriculture in the future. It can easily be transferred to other study areas (e.g. *Weinzierl* and *Heider* 2015). To ensure the progress of this approach, a more diverse set of climate models as well as additional input variables such as the length of the growing season and maximum and minimum temperatures should be included in future investigations.

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