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ORIGINAL ARTICLE

The suitability of *Macadamia* and *Juglans* for cultivation in Nepal: an assessment based on spatial probability modelling using climate scenarios and in situ data

Andrea Karin Barrueto[1,2] · **Jürg Merz**[2] · **Elias Hodel**[1] · **Sandra Eckert**[1,3]

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Abstract Global climate models predict temperature rises and changes in precipitation regimes that will shift regional climate zones and influence the viability of agricultural crops in Nepal. Understanding the influence of climate change on local climates and the suitability of specific sites for the production of individual crop types at present and in the future is crucial to increasing local crop resilience and ensuring the long-term viability of plantations—especially of high-value, perennial tree crops that require significant investment. This paper focuses on two cash crops, *Macadamia* and *Juglans*. A literature review summarises data on temperature, precipitation, and other macro- and microclimatic requirements of both genera. On this basis, we investigate the short- and long-term suitability of areas in Nepal for production of the two crops by means of a spatial model based on extensive in situ measurements, meteorological data, and climatic layers from the WorldClim dataset. Finally, we track changes in potential cultivation area under four Representative Concentration Pathways. Results show that climatic requirements for the cultivation of *Macadamia* and *Juglans* are fulfilled across a large part of Nepal at present and in the future: the total suitable area for both trees shrinks only marginally under all four scenarios. However, suitable areas shift considerably in spatial and altitudinal terms, meaning that some currently productive areas will become unproductive in the future, while currently unproductive ones will become productive. We conclude that the consideration of macro- and microclimatic changes in agricultural planning is essential to long-term agricultural success in Nepal.

Keywords Adaptation · Climate change · *Juglans* · *Macadamia* · Nepal · Spatial modelling

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✉ Andrea Karin Barrueto
andrea.barrueto@students.unibe.ch; andrea.barrueto@helvetas.org

Jürg Merz
juerg.merz@helvetas.org

Elias Hodel
elias.hodel@cde.unibe.ch

Sandra Eckert
sandra.eckert@cde.unibe.ch

1 Centre for Development and Environment, University of Bern, Hallerstrasse 10, 3012 Bern, Switzerland

2 HELVETAS Swiss Intercooperation, Av. Julius Nyerere No. 1213, Maputo, Mozambique

3 Department of Integrative Geography, Institute of Geography, University of Bern, Hallerstrasse 12, 3012 Bern, Switzerland

Introduction

Nepal is one of the most vulnerable countries among those that are likely to be severely impacted by climate change (Chen et al. 2015; Kreft et al. 2014; Wheeler 2011). Maximum temperatures in Nepal have been increasing since 1960, precipitation during the summer monsoon has been decreasing, and the monsoon onset has become increasingly unpredictable (GoN 2014; Kohler et al. 2014; McSweeney et al. 2010; Shrestha et al. 1999). The mean annual temperature is projected to rise further by 2060, most pronouncedly so in the western part of Nepal (McSweeney et al. 2010). Projected precipitation data indicate an increase in volume and intensity of rainfall in the monsoon (June–August) and post-monsoon (September–November) seasons, as well as a decrease in winter precipitation. In terms of geographical distribution, increases in summer rainfall are largest in the southeast of Nepal (NCVST 2009; McSweeney et al. 2010).

Changes in micro- and macroclimates are leading to more extreme weather events such as droughts and floods, and to changes in seasonal weather patterns (IPCC 2014). This is increasingly affecting agricultural systems and livelihoods in the Hindu Kush Himalayan region, where poverty is widespread (Karki and Gurung 2012; Pokhrel and Pandey 2013; Su et al. 2013). Agriculture is a major source of income for most people in this region: over 75% of Nepal's population depends on agriculture for self-sufficiency and income from cash crops (CBS 2012). Rural communities and people living in poverty have less capacity to cope with these effects and are therefore affected most (Dulal et al. 2010). Consequently, many people, especially young men, migrate to urban areas or abroad, causing an overall feminization of Nepalese agriculture (Sugden et al. 2014). According to Leduc (2009) and Mainlay and Tan (2012), women are especially vulnerable to climate change impacts, as they rely more heavily on natural resources for their livelihoods and are less able to access relevant information and adaptation skills.

The anticipated changes in climate and weather patterns worldwide have moved into the focus of research on food security, biodiversity, and cash crop production (Gornall et al. 2010; Hertel and Rosch 2010; Ranjitkar et al. 2014; Zomer et al. 2014). In the Nepalese context, Ranjitkar et al. (2015) outlined impacts of projected climate change on two cash crops, coffee and banana, that are cultivated mostly in plantations. Maharjan et al. (2013) examined how climate variables affect the yields of major food crops, suggesting that rice and potatoes will thrive under increased summer rain and temperatures, whereas other crops, such as maize and millet, will suffer.

Juglans (commonly known as walnuts) and *Macadamia* have recently gained popularity among farmers for enhancing food security and income. This is indicated both by the number of newly planted trees and by farmers' answers in an exploratory survey for this study. However, little is known to date about these trees' suitability for cultivation in Nepal's current and future climate. Trees are a long-term investment; accordingly, effective and sustainable agricultural planning in Nepal's rapidly changing environment depends on an improved understanding of climate change and its impacts on perennial horticultural crops. It is imperative to consider the effects of climate change in both national and local agricultural planning processes to enable informed decision-making and sustainable investments.

This research aims to contribute knowledge about the suitability of *Macadamia* and *Juglans* for cultivation in Nepal's current and future climate, and to predict suitable geographic regions for their cultivation. First, we assessed the current spatial distribution of *Macadamia* and *Juglans* trees in Nepal. Then, using meteorological and interpolated climatic datasets, we developed a geospatial model to delineate areas that are currently suitable for the cultivation of *Macadamia* and *Juglans*. Finally, we applied the model to four climate change scenarios (IPCC 2014) to delineate areas suited for future cultivation. We conclude with suggestions for applying our results under present and future scenarios.

Background

Macadamia spp. are evergreen trees, members of the Proteaceae family, and indigenous to Australia. The two edible species are *Macadamia tetraphylla* and *Macadamia integrifolia* (Chan 1983; Hamilton and Fukunaga 1959; Nagao et al. 1992). *Macadamia* was introduced to Hawaii in 1881, where it first became commercially important. Under a joint project of the Food and Agriculture Organization of the United Nations and the Australian and Nepalese governments, *Macadamia* was brought to Nepal in 1970 (Mascott Ltd. 1993; Upadhyay et al. 2003). Its primary habitat in Nepal is in the tropical and subtropical zones, although it can also grow in the temperate zone. The nut's history and early development in Nepal are only vaguely known (Pandey, personal correspondence, 2015). In the 1980s, *Macadamia* was recommended for cultivation as a cash crop that is well suited to Nepal's climate (Berg 1985).

The habitat of *Juglans* is the mountain ranges of Central Asia and the Himalayan region (Blaser et al. 1998; McGranahan and Leslie 1991; Molnar et al. 2011), where the nuts have been traded and the trees cultivated for several thousand years (Bemmann 1998; Crawford 1996). In the temperate and cold zones of Nepal, two types of *Juglans regia L.* are present: the indigenous so-called hard-shell walnut tree, formerly known as *Juglans regia* var. *kamaonia* (C. DC.) but today considered a wild form of *Juglans regia*, and the so-called soft-shell walnut tree, which is comprised mainly of cultivars and populations selected for crop production (Forestry Nepal 2016). The soft-shell or paper-shell walnut was introduced mainly from Kashmir (Jackson 1994), and there is a wide variety of cultivars that differ slightly in their climatic tolerance. *Juglans* is multifunctional: the nuts are collected and consumed at home, used for oil-making, or sold as a cash crop; the leaves, bark, and other parts are used as medicinal remedies, and the timber has always been considered valuable and is used for furniture (Bemmann 1998; Blaser et al. 1998; Kunwar et al. 2006; Rokaya et al. 2010; Taha and Al-wadaan 2011; Vahdati 2014).

For our fieldwork, we selected two geographic regions where adult, fruit-bearing trees are already established: the western part of Nepal for *Juglans* and the central part of Nepal for *Macadamia* (Fig. 1).

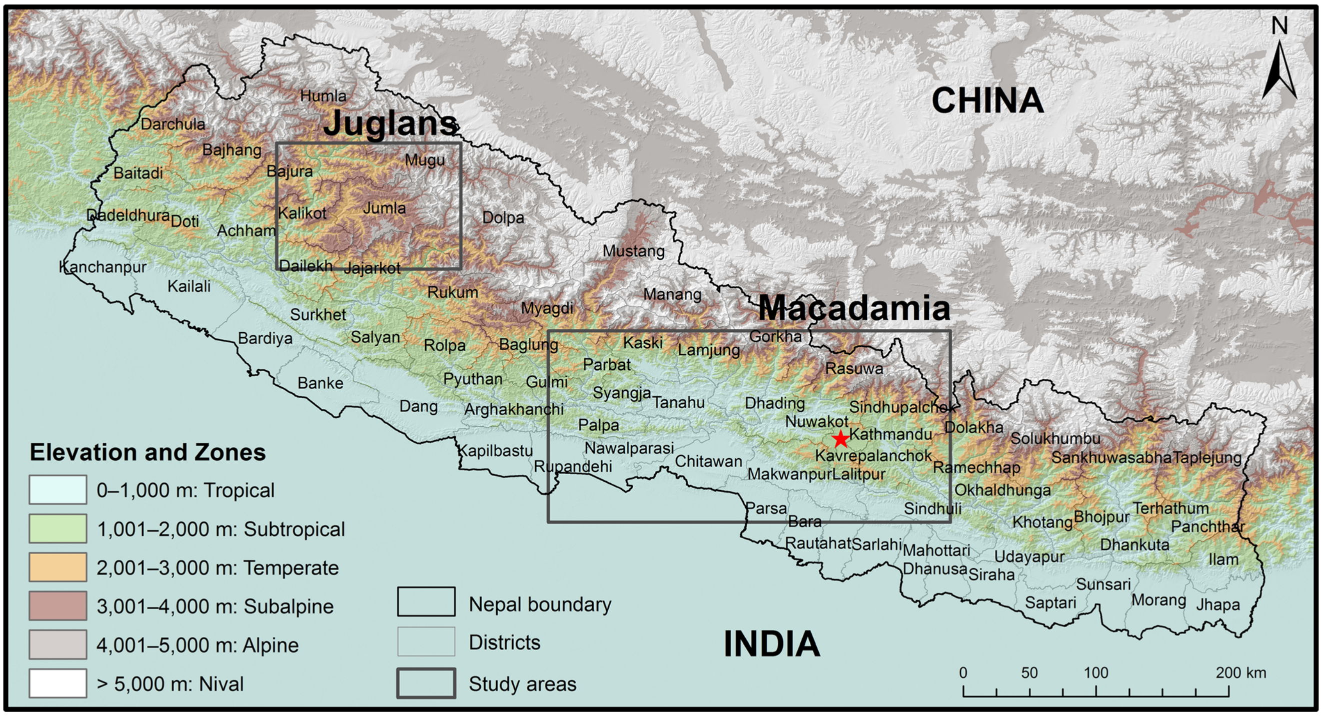

Fig. 1 Overview of study areas in Nepal

Materials and methods

Climate and geospatial datasets

The analysis of suitable areas for cultivation of *Macadamia* and *Juglans* under current climate conditions is based on the bioclimatic variables from the WorldClim dataset, version 1.4, developed by Hijmans et al. (2005). For the analysis of future suitable areas, we used climate data under an ensemble of four emission scenarios, the so-called representative concentration pathways (RCPs, van Vuuren et al. 2011a): RCP2.6, a stringent mitigation scenario (van Vuuren et al. 2011b), RCP4.5 and RCP6.0, two intermediate scenarios (Masui et al. 2011; Thomson et al. 2011), and RCP8.5, a scenario representing very high greenhouse gas emissions (IPCC 2014; Riahi et al. 2011; van Vuuren et al. 2011b). The RCPs cover the years 2035–2065 and thus represent a short- to medium-term timeframe. The four datasets were derived and scaled down to a spatial resolution of nearly 1 km by Zomer et al. (2014, 2015) using the Coupled Model Intercomparison Project of the fifth phase (CMIP-5) prediction (Ramirez-Villegas and Jarvis 2010; Taylor et al. 2012). The topographical analyses are based on the Shuttle Radar Topography Mission (SRTM) 90 m, version 4.1 digital elevation model. The administrative boundaries were taken from the Government of Nepal's regional database system. The meteorological data were provided by the Ministry of Population and Environment's Department of Hydrology and Meteorology and consist of national weather station records. A comprehensive description of the datasets used can be found in Appendix 1 online.

Research approach

The methodology consists of an iterative process using literature reviews, analysis of climatic and meteorological datasets, and in situ location and elevation measurements for both crops. The use of different data sources enables cross-validation of results from different perspectives (Fig. 2).

The study started with an exploratory review of academic and agricultural publications from around the world. The aim was to determine the climatic requirements for *Macadamia* and *Juglans* as genera, without focusing on a specific geographic area. In addition, we carried out a national survey among the Nepalese District Agricultural Development Offices to determine the areas in Nepal where *Macadamia* and *Juglans* trees are currently growing. However, this survey did not yield any information about *Macadamia*, as this crop is still fairly rare. In situ data were recorded using a GPS device. For the calibration of the preliminary model, we measured the location and elevation of 278 *Macadamia* trees at altitudes from 144 to 1550 m and of 525 *Juglans* trees at altitudes from 1149 to 2997 m (September to December 2014). For the validation of the final model, we gathered the location and elevation of 230 *Macadamia* trees at altitudes from 503 to 1624 m and 577 *Juglans* trees at altitudes from 1139 to 2977 m (April 2015 to May 2016). Histograms of the

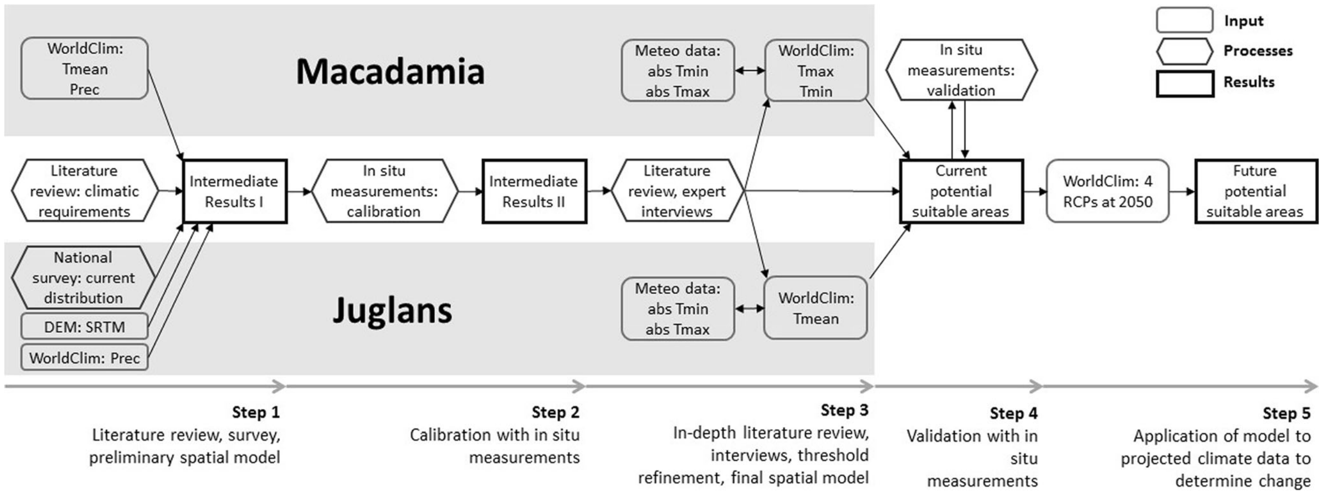

Fig. 2 Methodology for estimating and delineating potential *Macadamia* and *Juglans* cultivation areas

elevational distribution of *Macadamia* and *Juglans* in situ measurements used to calibrate and validate the models are provided in Appendix 2 online.

Spatial modelling process

The information from the literature review and the survey was used to guide the selection of predictor variables and threshold values for a preliminary spatial model of areas currently suited for the cultivation of *Macadamia* and *Juglans* in Nepal. For *Macadamia*, we selected annual mean temperature (Tmean) and annual precipitation (Prec) from the WorldClim dataset as predictor variables; for *Juglans*, we selected elevation from the SRTM digital elevation model and Prec (Fig. 2, Step 1). Threshold values were set to divide the area of Nepal into three categories: "too cold", "suitable for cultivation", and "too hot". A first run of our model led to Intermediate Result I, which we used to choose our fieldwork areas. Within these areas, we recorded the coordinates of adult flowering and fruit-producing trees, assuming that a suitable macroclimate for production existed only where the trees encountered were nut-producing. These in situ measurements (Appendix 2a) were then used to calibrate our model by adjusting the threshold values until all in situ points lay inside the area categorised as suitable (Fig. 2, Step 2, Intermediate Result II). On this basis, and after a more in-depth literature review complemented by interviews with selected authors, we developed a new model using different predictor variables and refined threshold values to divide the area of Nepal into five suitability categories. This model was based on minimum temperature of the coldest month (Tmin) and maximum temperature of the hottest month (Tmax) for *Macadamia* and Tmean for *Juglans* (Fig. 2, Step 3, Result I). WorldClim data were used for both crops to enable prediction of changes under future climate scenarios in a later step. The WorldClim dataset does not contain absolute monthly extreme values (see "Limitations of the datasets" below); however, its adequacy was confirmed by a comparison of our results with the absolute daily minimum (abs Tmin) and maximum temperatures (abs Tmax) measured at the 117 national meteorological stations in Nepal from 1956 to 2009 (see Appendix 3 online for a description of the weather stations and the respective temperatures). Next, we validated this second model using the second set of in situ measurements, which were collected with a focus on the category boundaries, at particularly low and particularly high elevations (Fig. 2, Step 4). Applying our validated threshold values to the projected climate data from Zomer et al. (2014), we then modelled the areas suitable for growing both crops in 2050 under each of the four RCPs (Result II). Finally, we calculated and visualised the changes in area and the shifts in elevation of suitable areas for growing the selected crops between now and 2050 under each of the four RCPs (Fig. 2, Step 5).

Limitations of the datasets

The topography of Nepal ranges from flat plains to mountainous, deeply fissured reliefs. The chosen SRTM digital elevation model with a resolution of 90 m approximates to reality. The WorldClim dataset's resolution of 1000 m is less detailed, especially in regions with steep slopes and narrow valleys, and it does not reflect microclimatic situations. Moreover, the dataset contains monthly average values, and absolute extreme values are therefore missing. Understanding these extremes is crucial for successful cultivation of both crops. Despite these limitations, the WorldClim dataset is the best-developed dataset available for Nepal (Ranjitkar et al. 2015, 2016; Zomer et al. 2014, 2015). In addition, it is also the basis of the projected climate scenarios (Taylor et al. 2012) averaged by Zomer et al. (2014). Wind, humidity, soil qualities, radiation, chilling hours, and growing season days also influence cultivation of the trees, but data on these parameters are only available in very limited form for the current climate. We therefore decided to work with the two climatic requirements of temperature and rainfall only, without considering microclimatic requirements.

Results and discussion

Suitable climatic conditions for *Macadamia* cultivation

A detailed summary of our literature review regarding climatic conditions for *Macadamia* cultivation is given in Appendix 4 online. The best-described climatic parameter for *Macadamia* is a Tmean ranging from 13 to 30 °C. Regarding winter temperatures, researchers suggested an abs Tmin of − 6–0 °C to be tolerable for adult trees, with lower temperatures being lethal; the range for Tmin is 0–15 °C. Cool temperatures induce flowering in *Macadamia*, and the reported minimum temperatures required for floral induction vary from 5 to 20 °C (Moncur et al. 1985; Nakata 1976; Stephenson and Gallagher 1986). Under Australian conditions, the first racemes emerge in mid-autumn (Moncur et al. 1985); however, the distribution of raceme initiation/emergence throughout late autumn and winter has never been sampled. Out-of-season flowering is observed, but the stimulus remains unknown (Wilkie, personal correspondence, 2016). In summer, *Macadamia* trees will grow healthily with a Tmax of 30–38 °C and an abs Tmax not exceeding 38–46 °C; resistance to heat waves of up to 46 °C is contingent on sufficient water availability (Morrow 2007). Trees in hotter climates will have lower kernel recoveries (i.e. thicker shells), but with sufficient water availability can still produce fairly good crops (Jones, personal correspondence, 2015). Looking at precipitation, studies suggest a tolerable annual rainfall of 510–4000 mm. With Nepal's average annual rainfall ranging between 1000 and 3000 mm, precipitation is assumed not to be a limiting factor. The tolerable range of precipitation is additionally influenced by the availability of irrigation, the composition of soils, and evaporation. The current *Macadamia* growing areas are dominated by cambisols and luvisols (FAO 2016). The former is high in weatherable minerals and low in clay, while the latter has a mixed mineralogy, high nutrient content, and good drainage; both are generally suitable for a wide range of agricultural uses, including nut production.

Suitable climatic conditions for *Juglans* cultivation

The cultivation of *Juglans* has a long tradition in different climatic conditions. A detailed summary of the climatic conditions for *Juglans* cultivation based on our literature review is provided in Appendix 5 online. The lowest abs Tmin adult trees have been observed to endure is − 40 °C, with a recommended Tmin of − 3–10 °C. Most authors suggest a Tmean of 7–15 °C. Because *Juglans* is a deciduous tree, fruit development requires a certain number of days above a certain temperature. According to the literature, *Juglans* requires a growing season of 120–280 days with a daily mean temperature consistently over 0–10 °C (Becquey 1997; Kolov 1998; Mettendorf et al. 1996; Pretzsch 1995; Putinică 2012; Vahdati, personal correspondence, 2016). Unlike the literature on *Macadamia*, that on *Juglans* offers no information on Tmax and only scarce information on Tmin, both of which we therefore excluded from our analysis. This climatic information is congruent with the elevations retrieved from the national survey, according to which *Juglans* have been observed to grow at 1100–3000 m in Nepal. Individual trees have been reported to grow at 800–1100 m and at 3000–3200 m. The overall annual chilling requirement (chilling hours), defined as the minimum period of cold weather after which a fruit tree will blossom, is important for crop growth. During these cold months, the tree is dormant and needs no water until the air temperature rises to at least 10 °C and the vegetation period starts (Rudow, personal correspondence, 2014). Pope and Vahdati (both personal correspondence, 2016) recommend that the number of chilling hours should range between 300 and 1800. Researchers indicate that minimum annual precipitation levels ought to exceed 600 mm; Molnar et al. (2011) is an exception, suggesting a minimum of 250 mm. Lower values are possible if irrigation or another alternative water source is available; for example, nearby rivers increase the level of groundwater, making it accessible to *Juglans*' deep roots and reducing the trees' dependency on precipitation. Regosols and cambisols prevail in the regions where *Juglans* currently grow in Nepal (FAO 2016). While regosols rarely store nutrients and water, they offer high permeability for roots, good aeration, and the ability to warm up. Their inability to store water is expected to become problematic if dry seasons become more extreme under the predicted climate changes. Cambisols, as mentioned above, are good agricultural soils due to their high nutrient content.

Modelling areas suitable for *Macadamia* and *Juglans* cultivation

The information from the literature review and the national survey (see "Suitable climatic conditions for *Macadamia* cultivation" and "Suitable climatic conditions for *Juglans* cultivation") provided the basis for a preliminary spatial model using Tmean and Prec for *Macadamia* and elevation and Prec for *Juglans*. Given that *Macadamia* is still rare in Nepal, we could collect only a limited number of in situ measurement points based on spatial mapping of the information from the literature review. *Juglans*, in contrast, is indigenous and therefore widely spread across all of Nepal. Calibration of the threshold values using the first set of in situ measurements, along with a more in-depth literature review and interviews with selected authors, led us to develop a new model using different predictor variables and refined threshold values. Table 1 shows refined

Table 1 Refined threshold values for *Macadamia* and *Juglans* cultivation (italicised script indicates variables/values used in final model)

	Macadamia			*Juglans*		
Category	Adverse	Moderate	Optimal	Adverse	Moderate	Optimal
Abs Tmin [°C]	< − 6	− 6–2	> − 2	< − 22	− 22–2	> − 2
Tmin [°C]	< *1*	*1–4*	> *4*	–	–	–
Tmean [°C]	< 11	11–15	15–30	< *7.5* > *21*	*7.5–9* *19.5–21*	*9–19.5*
Tmax [°C]	> *38*	*32–38*	< *32*	–	–	–
Abs Tmax [°C]	> 45	39–45	< 39	> 44	38–44	< 38
Prec [mm]	< 500	500–1000	1000–4000	< 400	400–600	> 600

threshold values for all variables considered; italicised script indicates the variables and values employed in the final model. To overcome the limitation of missing absolute monthly extreme values in the WorldClim dataset, we compared the suitability categorization based on the derived absolute daily minimum and maximum temperature values measured at the 117 meteorological stations in Nepal from 1956 to 2009 with that based on the monthly averages contained in the WorldClim dataset. The two categorizations proved to be fairly congruent (80% congruence for *Macadamia*, 99.5% for *Juglans*), indicating that use of the WorldClim monthly averages is adequate. The upper threshold of the optimal Tmean for *Juglans* at 19.5 °C was derived from the elevation range obtained from the national survey, assuming that this information accurately reflects the suitable elevation and temperature range for *Juglans* production in Nepal.

The validation of our modelling results using the second set of in situ measurements (Appendix 2b) showed that all locations of trees found in the field fell within the areas anticipated as suitable for cultivation by our model, thus confirming its accuracy.

Potential cultivation areas under current climate conditions

Figure 3 below depicts current and future potential *Macadamia* and *Juglans* cultivation areas. For each crop, our model divides the area of Nepal into five categories: “too hot”, “moderately suited/warm”, “optimal”, “moderately suited/cool”, and “too cold”. As the naming suggests, crop growth is expected to be best in areas categorised as “optimal”; in “moderately suited/warm” and “moderately suited/cold” areas, site evaluation should include a careful assessment of microclimatic conditions and climate change impacts to determine suitability.

According to our model, areas with an “optimal” climate for *Macadamia* cultivation cover approximately 25,034 km^2 or 17.01% of Nepal and are found at an average elevation of 1167 m (Table 2). *Macadamia* is most successfully grown in tropical and subtropical climates (Fig. 3a). Most of these “optimal” areas lie in Central and Eastern Nepal. In the tropical area—the terai—*Macadamia* grows moderately well, but growth is limited by the hot summer temperatures especially in the western districts. This “moderately suited/warm” category covers approximately 42,023 km^2, or 28.55% of the country, at a mean elevation of 374 m. The climate in the north is cooler due to the high mountains, and moderate growth is indicated as possible at an average elevation of 1786 m within this subtropical zone. This is congruent with the fact that the highest *Macadamia* tree we encountered in the field grew at 1624 m. The “moderately suited/cool” area corresponds to 17,947 km^2, or 12.19% of Nepal (Table 2).

For *Juglans*, our model indicates that the “optimal” climate falls within the subtropical and temperate climate zones (Fig. 3b). This “optimal” area for *Juglans* cultivation covers 48,346 km^2, or 32.85% of Nepal, at an average elevation of 1911 m and is concentrated primarily in the western districts. The “moderately suited/warm” category covers 9919 km^2 or 6.74% of Nepal at a mean elevation of 971 m. In the southern districts, warm summer temperatures and the absence of a cold season limit the cultivation of *Juglans*. The “moderately suited/cool” category comprises an area of 4129 km^2 or 2.81% of Nepal at an average elevation of 3233 m. In the north, the cold temperatures of the high mountains are a natural barrier to growth. Precipitation is not a limiting factor for *Juglans* growth in Nepal: annual precipitation levels are optimal (> 600 mm) wherever temperature requirements for successful *Juglans* cultivation are fulfilled. The only exception to this was found in the Mustang district in central Nepal, which lies north of two mountain ranges, in a rain shadow with very low annual precipitation levels (< 400 mm). All *Juglans* trees we recorded in Mustang grow in the valley bottom near the Kali Gandaki river, which ensures sufficient water supply. Overall, however, temperature ranges are currently the only limitations to *Juglans* growth in Nepal. This is especially important in view of future climate and temperatures changes.

Potential cultivation under future climate scenarios, and recommendations

According to Shrestha et al. (2012) and Xu et al. (2009), the results of the CMIP-5 multimodel ensemble of emission scenarios generally agree with the climate trends recently

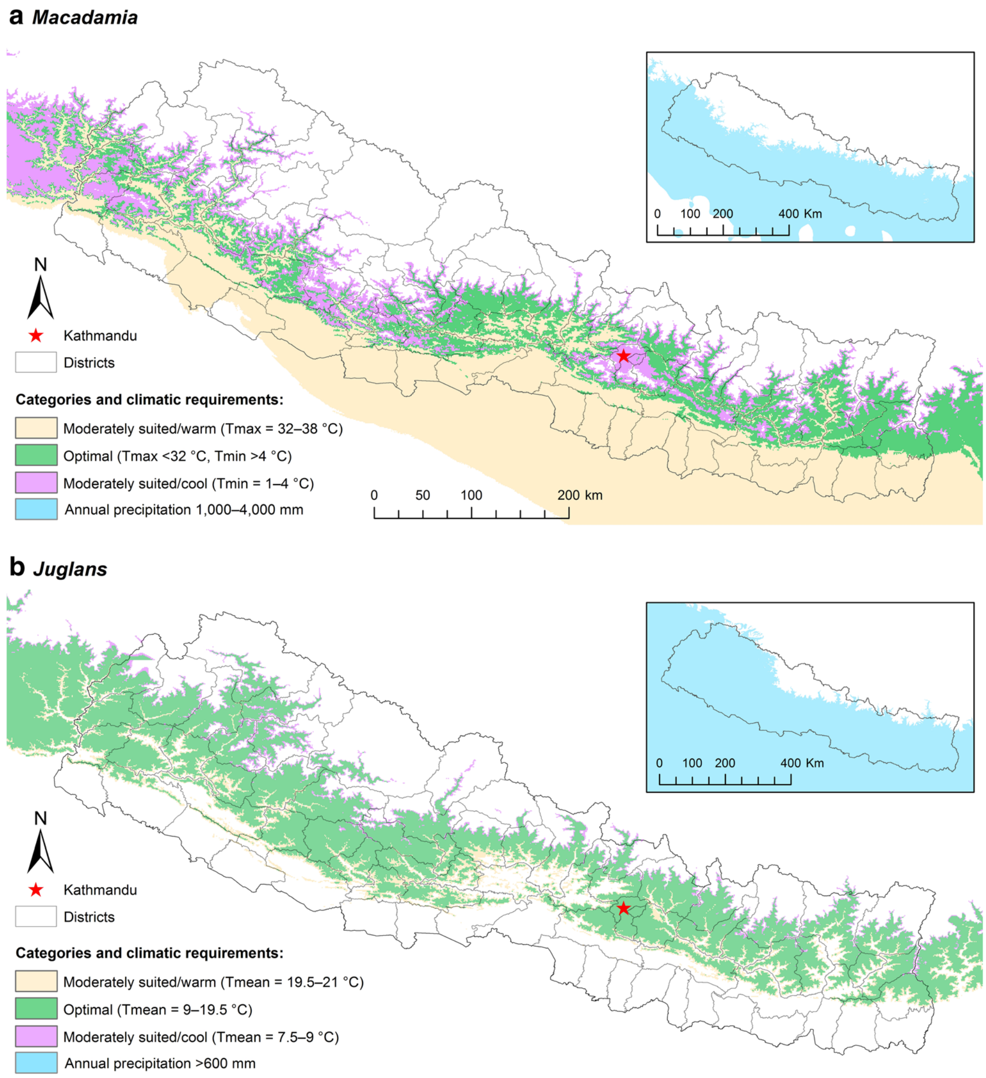

Fig. 3 Current potential area of (**a**) *Macadamia* and (**b**) *Juglans* cultivation based on temperature and precipitation

observed in Nepal. Annual mean temperatures are expected to increase over all of Nepal; under all of the RCPs, the rate of warming is most likely to accelerate and the climate to become hotter. Precipitation volumes will likely increase slightly, peaking under RCP6.0.

Figure 4 presents the consequences of the expected climate changes under the four RCPs for the cultivation of *Macadamia* and *Juglans* in Nepal. The areas where growth conditions are expected to deteriorate or improve in the future are shaded in different colours: (1) red denotes areas that are currently "moderately suited/warm" and are projected to become "too hot"; (2) orange denotes areas where the climate is "optimal" at present and is projected to become "moderately suited/warm"; (3) light green denotes areas that are currently "moderately suited/cool" and are projected to become "optimal"; and (4) dark green denotes areas that are "too cold" at present and are projected to become "moderately suited/cool".

The biggest changes in current potential *Macadamia* growing areas are expected to happen in the southwestern districts, where regions that are currently "moderately suited/warm" are expected to become "too hot" for production under all four climate scenarios (Fig. 4a–d). The southeastern district is projected to remain "moderately suited/warm". The central areas (Kaski and Tanahu districts) will experience warming and move from the "optimal" to the "moderately suited/warm" categories. The Kathmandu valley in central Nepal, the western districts (e.g. Arghakhanchi, Gulmi, Parbat, Pyuthan, Rolpa), and the far-western districts (e.g. Baitadi, Dadeldhura, Doti) will gain productive area: "moderately suited/cool" conditions will become "optimal". The "moderately suited/cool" cultivation areas at higher elevations are expected to expand to still higher elevations.

Table 2 shows changes in the areas suitable for *Macadamia* cultivation. Gains for the "optimal" category are marginal at 1.16% under RCP2.6, 0.84% under RCP4.5, 1.7% under RCP6.0, and 1.19% under RCP8.5. Area gains for the "moderately suited/warm" category are slightly larger at 2.31%

Table 2 Potential *Macadamia* and *Juglans* cultivation areas in Nepal in 2000 and under RCP2.6, RCP4.5, RCP6.0, and RCP8.5

	Category	2000				RCP2.6				RCP4.5				RCP6.0				RCP8.5			
		km²	%[a]	m[b]	STD	km²	%	m	STD	km²	%	m	STD	km²	%	m	STD	km²	%	m	STD
Macadamia	Too hot	3719	2.5	183	31.3	12,443	8.5	211	127.8	16,139	11.0	226	147.7	13,364	9.1	212	130.2	18,950	12.9	240	167.5
	Mod. to warm	42,023	28.6	374	294.1	45,417	30.9	570	396.1	44,291	30.1	630	414.2	44,988	30.6	583	398.8	44,186	30.0	689	432.8
	Optimal	25,034	17.0	1167	309.9	26,743	18.2	1525	342.2	26,275	17.9	1599	347.0	27,529	18.7	1555	352.4	26,791	18.2	1696	365.9
	Mod. to cold	17,947	12.2	1786	315.7	13,267	9.0	2286	351.7	12,948	8.8	2387	354.6	12,842	8.7	2338	355.0	12,224	8.3	2553	360.3
	Too cold	58,458	39.7	3998	1138.7	49,310	33.5	4294	979.4	47,528	32.3	4354	944.9	48,459	32.9	4323	963.0	45,030	30.6	4437	898.3
	Suitable area	85,004	57.8			85,427	58.04			83,514	56.74			85,358	58.0			83,201	56.53		
Juglans	Too hot	45,975	31.2	341	248.9	57,413	39.0	471	348.4	60,617	41.2	509	376.0	58,581	39.8	484	358.4	63,761	43.3	547	403.6
	Mod. to warm	9919	6.7	971	128.5	9857	6.7	1276	133.2	9828	6.7	1362	136.0	9839	6.7	1307	134.2	9753	6.6	1448	145.0
	Optimal	48,346	32.8	1911	579.3	42,396	28.8	2263	629.2	40,632	27.6	2370	640.5	41,599	28.3	2296	629.5	39,014	26.5	2482	650.2
	Mod. to cold	4129	2.8	3233	269.6	9879	6.7	3811	351.2	3800	2.6	3694	299.7	3845	2.6	3631	314.4	3707	2.5	3788	299.0
	Too cold	38,812	26.4	4647	775.7	27,637	18.8	5001	596.1	32,304	21.9	4855	666.1	33,317	22.6	4823	682.7	30,946	21.0	4897	645.2
	Suitable area	62,394	39.4			62,131	42.2			54,259	36.9			55,283	37.6			52,474	35.7		

[a] Percentage of total area of Nepal (147,181 km²)

[b] Average elevation in metres

under RCP2.6, 1.54% under RCP4.5, 2.01% under RCP6.0, and 1.47% under RCP8.5. Together, these gains partly balance out area losses in the "moderately suited/cool" category (− 3.18% under RCP2.6, − 3.4% under RCP4.5, − 3.47% under RCP6.0, and − 3.89% under RCP8.5). The increase in the "moderately suited/warm" category is explained by the flatter terrain at lower elevations, while the increasing steepness of the terrain at higher elevations accounts for the losses in the "moderately suited/cool" category. Overall, there is only a marginal change in the size and geographic location of the three categories suitable for *Macadamia* nut production (0.29% under RCP2.6, − 1.01% under RCP4.5, 0.24% under RCP6.0, and − 1.22% under RCP8.5). However, each RCP indicates an upward shift in the suitable areas' average elevation; the extent of this shift depends on the geographic location of the area and ranges from 350 to 500 m.

Consequently, when choosing a cultivation area in a marginal region that is likely to change under future climate conditions, especially at lower elevations, the microclimate must be carefully assessed and precautions taken so that trees are not planted in areas that are expected to become inhospitable for *Macadamia* cultivation due to temperature-induced stressors. Periods of exceptionally hot temperatures can be bridged with sufficient irrigation, as studies in Australia have shown (Morrow 2007). Other research shows that consistently high temperatures tend to inhibit vegetative growth and may induce leaf yellowing or chlorosis, which potentially reduces production, especially under conditions of low humidity and moisture stress (Stephenson and Trochoulias 1994). However, Williams et al. (2006) suggest that vegetative flushing correlates with temperature, available water, and sunlight, and enough soil moisture is needed during the summer vegetative flush. Furthermore, Wilkie (personal correspondence, 2016) underlines the importance of sufficient soil moisture throughout the year and particularly throughout the crop development period for best yields. At the same time, the soil must not be waterlogged, as flooding or waterlogging for more than 5 consecutive days might harm the plant (Trochoulias and Johns 1992; Williams et al. 2006). Sites at higher elevations have to be chosen carefully to avoid climates with low winter temperatures (Shigeura 1981). Pest risks may also change under altered climate conditions. For example, various studies (Cull and Trochoulias 1982; Nagao 2011; O'Hare et al. 2004; Trochoulias and Lahav 1983) show that blossom blight is common when cool temperatures and high humidity coincide with the flowering period. However, as Nepal's precipitation regime is driven by the summer monsoon, which peaks in the warm months of June, July, and August, the threat of pests to *Macadamia* production is minimal under the RCPs we studied. To the contrary, the summer rains can be expected to foster high yields. This further confirms the suitability of *Macadamia* for sustainable agricultural production in Nepal both at present and under future climate scenarios.

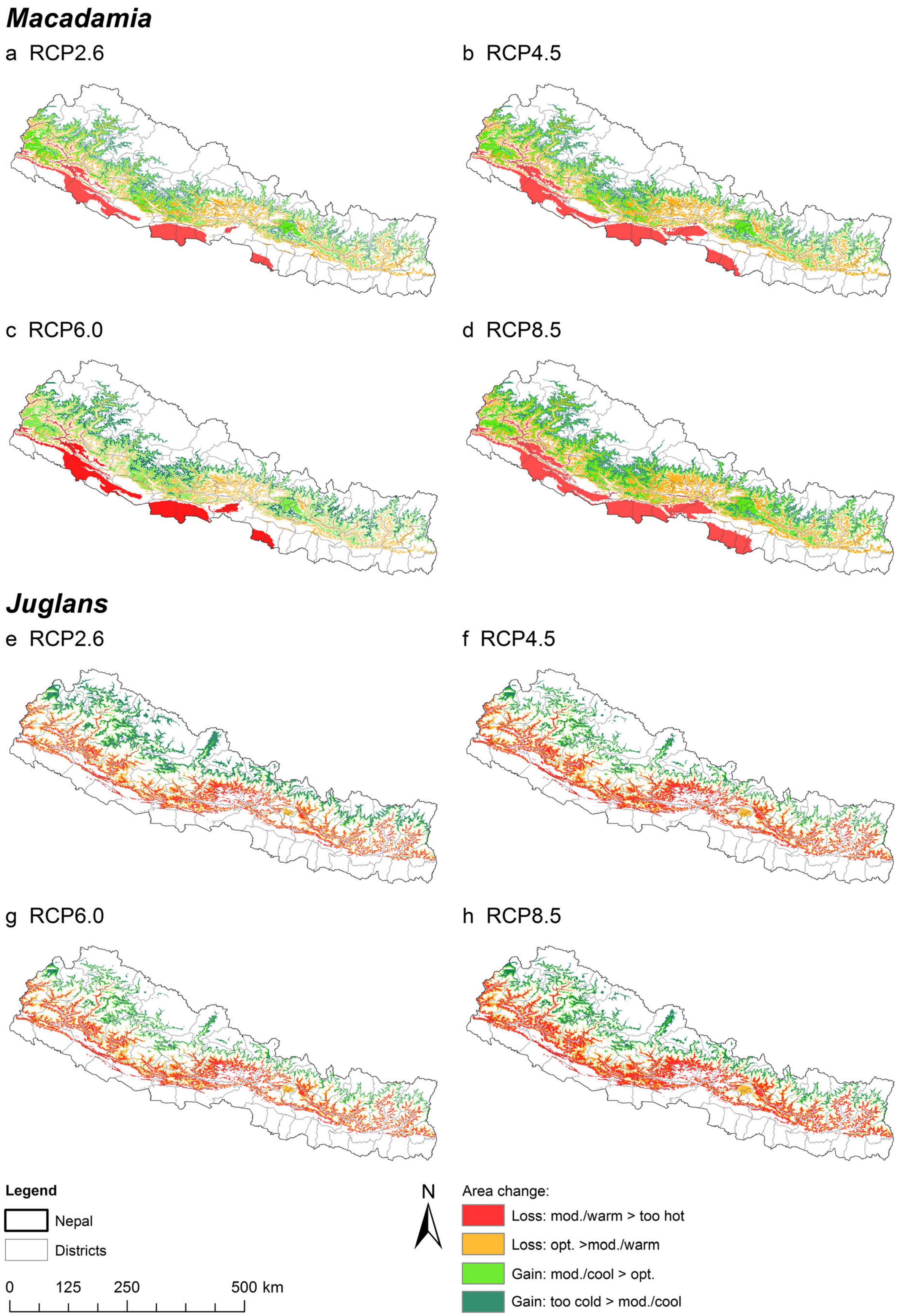

Fig. 4 Changes in potential *Macadamia* (**a**–**d**) and *Juglans* (**e**–**h**) cultivation area under RCP2.6, RCP4.5, RCP6.0, and RCP8.5

Figure 4e–h depicts the expected changes in areas suited for *Juglans* cultivation. The biggest changes occur in the central to western subtropical zone: areas currently in the “moderately suited/warm” category are expected to become “too hot”, and areas that are currently considered “optimal” will become “moderately suited/warm” under all RCPs. The loss of currently suitable areas is most noticeable under RCP8.5 (Fig. 4h). However, it is partly offset by an expansion of the suitable area in the temperate and subalpine zones. Once again, this change is more pronounced in the central and western districts; in particular, our model shows that potential cultivation areas are likely to expand in the north to central district of Mustang and in the western district of Darchula, where regions that were previously categorised as “too cold” will become “moderately suited/cool”, thus enabling *Juglans* cultivation. The exact changes in area for *Juglans* are shown in Table 2. Areas currently categorised as “optimal” will shrink under each scenario we modelled, at an average of − 5%. The losses are − 4.04% under RCP2.6, − 5.24% under RCP4.5, − 4.58% under RCP6.0 and − 6.34% under RCP8.5. The “moderately suited/warm” category is expected to change only marginally, with an average loss of less than − 0.1%. Interestingly, the changes for the “moderately suited/cool” category differ under the various RCPs. While this category is projected to gain 3.91% under RCP2.6, it will shrink by − 0.22% under RCP4.5, − 0.19% under RCP6.0, and − 0.29% under RCP8.5. As shown in Table 2, the average elevation will shift upwards by 130 to 600 m under the various RCPs. Overall, the loss of suitable area for *Juglans* cultivation exceeds gains under all RCPs, with a maximum net loss of 6.8% (corresponding to a reduction from 62,394 to 52,474 km^2) under RCP8.5.

We therefore advise planters of *Juglans* orchards to confirm the planned locations’ suitability regarding summer temperatures using locally available weather data; this is particularly important when developing prospective larger orchards at lower elevations (1100–1500 m). Our model shows that areas at this elevation are likely to become “too hot” under any of the four climate scenarios. By contrast, cold winter temperatures do not seem to be a problem in Nepal, as the lowest absolute minimum temperature recorded between 1953 and 2009 was − 26 °C (in the Mustang district). As discussed above, research shows that *Juglans* can endure significantly lower temperatures, such as − 33 to −37 °C in the USSR, − 35 to − 40 °C in the Carpathian Mountains of Poland, and − 37 °C in China (Smith 1950; Smith and Allinger 1969; Xi 1985, all cited in McGranahan and Leslie 1991). However, *Juglans* is susceptible to late frost in spring which may kill its growing parts and thereby severely affect production (Barengo 2001; Becquey 1997; Hemery and Popov 1998; Tshering 2007). It is therefore important to include microclimatic conditions in orchard planning (Barengo 2001; Becquey 1997; Rudow, personal correspondence, 2016; Tshering 2007): in general, wind-protected south or west slopes offer optimal microclimatic conditions. Close to the upper altitudinal limit of production, two settings should be avoided in view of the risk of late frost: one is topographic cold-air accumulation zones (such as depressions) and cold-air discharge channels in mountain flanks, where late frost events are more probable; and the other is southern expositions, where trees often show premature sap flow and are therefore more susceptible to damage in the event of late frost. In sum, careful, strategic planning considering both macro- and microclimatic variables will be required to sustain widespread, long-term cultivation of *Juglans* trees in Nepal.

Conclusion

Our spatial model delineates the geographic boundaries of both current and potential future suitable areas for the cultivation of two tree crops, *Macadamia* and *Juglans*, in Nepal based on existing literature, meteorological data, in situ measurements, and the modelled climate data of the WorldClim dataset. The model was validated using absolute values from national meteorological stations and in situ measurements, which were used to confirm the appropriateness of the selected threshold values applied to the WorldClim data. Our modelling results confirm that the current climate in Nepal is suitable for widespread *Macadamia* and *Juglans* cultivation. Our findings, along with careful consideration of the microclimatic and soil conditions on each farmer’s land, can guide investment in planting additional trees. However, if nut production is to be sustained under expected future climate changes, it is imperative that the projected shifts in macroclimatic zones, the temperature changes within each region, and microclimatic conditions are carefully assessed and considered when developing existing orchards and before planting new ones. This is particularly important at the margins of the currently suitable cultivation areas. Projections under the four emission scenarios for the short term—that is, for 2050—indicate that climatically suitable areas for *Macadamia* will continue to account for approximately 57% of Nepal’s area, but will shift upwards in elevation by 350–500 m. Geographically, the biggest changes are to be expected in the southwestern districts bordering India, where part of the current potential *Macadamia* cultivation area will become unusable due to summer heat. Much of this loss will be offset as conditions in the higher subtropical areas become optimally suited for *Macadamia* cultivation. These expected gains are most pronounced in the western districts of Dadeldhura and Doti, the central districts of Rolpa and Parbat, and the Kathmandu valley. Regarding *Juglans*, however, our model predicts a considerable net loss of potential cultivation area under all four climate scenarios due to increased temperatures; the worst loss of up to 6.8% is predicted under RCP8.5. At the same time, suitable areas will move 130–600 m upwards in terms of elevation. However, spatial changes are less pronounced than for *Macadamia*; large-scale shifts are expected to occur only in the mid-western districts. We conclude that both crops can be grown successfully under all RCPs, provided that these regional climatic shifts are taken into account before planting. We acknowledge that the climate projections for 2035–2065 will take time to unfold; this means that suitable cultivation sites under future climate scenarios at higher elevations currently still experience cold Tmin, which presents a risk to trees planted now and to the volume of their harvests.

To improve the applicability of our model in local planning processes, we suggest that further research should examine the effects of new crops like *Macadamia* and *Juglans* on smallholder farmers and their livelihoods. Questions of cultural suitability, workload, economic value, market access, and gender perspectives will provide further insights into the appropriateness of each region for new orchards. On a national scale, we recommend research into the influence of expected climate changes on microclimatic and soil conditions such as humidity, soil pH, soil texture, or wind. We also suggest investment in studies that review and apply best practices of planning, selecting, and cultivating the best crop varieties for Nepal's climate. Finally, at a strategic level, we strongly recommend an investigation into the impact of climate change on the current land use policy and its implications for agriculture in Nepal. With careful planning, both *Macadamia* and *Juglans* could support sustainable agriculture in Nepal for a long time to come.

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