



Original Research Articles

Navigating climate change: Impacts on indigenous practices concerning agrifood systems in Nepal's socio-ecological landscape

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ABSTRACT

Climate change, its consequences, and related adaptation and mitigation strategies have been widely discussed in recent decades. However, the impacts of climate change on indigenous and local communities, their cultural adaptation practices, and the integrity of agrifood production systems have received limited attention. This study addresses this gap by examining the perspectives of forest-dependent local stakeholders (FDLS) in Nepal's lowland landscape. Using a participatory research approach, we analyzed empirical climatic data to assess the threats climate change poses to the cultural practices of indigenous and local peoples. We explored the adaptation strategies employed by these communities within the socio-ecological systems (SES) framework. Data collection involved semi-structured interviews (n = 136), focus group discussions (n = 9), and expert interviews (n = 27) across selected districts, complemented by secondary sources such as policy documents, district profiles, and climate reports. Our findings reveal significant climatic changes, including rising temperatures, earlier summers, shorter winters, unpredictable monsoons, increased droughts and wildfires, and water shortages. These changes have forced FDLS to adopt less water-intensive, drought-tolerant, insect-resistant, and hybrid crop varieties. However, these adaptation strategies often come with additional costs, labor, time, and technological demands, impacting livelihoods and contributing to cultural disintegration. Moreover, these changes have jeopardized food systems and eroded long-standing local traditions tied to sustainable livelihoods. This underscores the urgent need to strengthen ecosystem and community resilience to safeguard food security and the environment in the face of climate change. Our findings highlight site-specific impacts and adaptation strategies, the challenges to indigenous practices and cultural preservation, and policy pathways to address these issues.

1. Introduction

The impacts of climate change are evident across both social and natural systems. Scientific data and people's experiences illustrate the impacts on the atmosphere, oceans, mountains, and land. This underscores the sensitivity of both natural and human systems to shifting climate patterns (IPCC, 2014; Pant et al., 2023). The 6th assessment report of the Intergovernmental Panel on Climate Change (IPCC) cautioned that the frequency and severity of climatic extremes, along with their consequences, are projected to worsen as the atmosphere,

ocean, and land continue to warm (IPCC, 2021; Pandit et al., 2021). Even though such impacts differ across geographical, socio-political, and economic contexts (MEA, 2005), the least developed countries with subsistence livelihoods are most vulnerable and disproportionately impacted (Klein, 2009; Pandey et al., 2024b, c). Nepal, despite being one of the least developed nations and making a minimal contribution to global greenhouse gas emissions, faces significant impacts from climate change (Eckstein et al., 2019; Pandey et al., 2024b; Paudel et al., 2020). A study report indicates that climate change is expected to persist throughout the 21st century, with mean temperatures projected to

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increase by 0.9–1.1 °C by 2050 and 1.3–1.8 °C by 2100 (MoFE, 2019). Research suggests that temperatures are increasing at a rate of 0.06 °C per year. This trend is particularly concerning in Nepal's Terai region, where crops are highly sensitive to even slight changes in climate conditions (Shrestha and Aryal, 2011). This indicates that future climate changes may further pose threats to traditional food production systems.

Changes in climate have profound implications for agriculture, livestock farming, and forest systems due to their high sensitivity to temperature and rainfall variations (Aryal et al., 2020, 2016; Shrestha and Aryal, 2011). Understanding local climate change is crucial because livelihoods are deeply interconnected across these systems. In Nepal, over two million people rely on agriculture, which is closely linked to forests and water ecosystems for various resources (Acharya et al., 2019; Aryal et al., 2023a). The ways and practices of obtaining goods and services vary from place to place and across different communities (Acharya et al., 2019; Aryal et al., 2023b). Practices for accessing these resources vary among communities, shaping unique traditions, beliefs, knowledge, and customs that form the cultural fabric of each community (UIA, 2023; White, 1959). This cultural identity fosters a deep connection between people and their environment, influencing perceptions of climate change (Clayton et al., 2015). Indigenous and traditional knowledge accumulated over generations provides valuable, context-specific solutions to environmental challenges (Ives et al., 2003).

Moreover, since perceptions often reflect local climatic conditions (Ayanlade et al., 2017), they are vital for shaping effective climate policies (Bogdan et al., 2016; Lujala et al., 2015). Policies informed by local knowledge and experiences can effectively address climate change risks (Hamilton and Keim, 2009; Nguyen et al., 2016; Pandey et al., 2023). Assessing community perceptions is, therefore, essential not only to understand climatic phenomena and their impacts but also to value local knowledge and experiences, enabling more responsive climate actions (Devkota et al., 2017) and the adoption of site-specific adaptation strategies across socio-ecological landscapes (Pandey et al., 2023; Sylliris et al., 2023). This participatory, locally perceived approach is particularly crucial in Nepal and similar geographies due to its wide range of microclimatic variations within small areas and limited meteorological stations for long-term data collection and generalization of climate patterns (Budhathoki and Zander, 2020; DHM, 2017; Marino et al., 2023; Sylliris et al., 2023). Also, it would be valuable to compare extreme climate indices from available observed climatic phenomena records (DHM, 2017) to corroborate evidence alongside perceived climate dynamics for the credibility of climatic facts and realized instances in the ground. This combined approach establishes a robust understanding of climatic phenomena and their impacts, particularly on culturally integrated, traditionally adopted livelihood strategies related to food and livestock production, and their interactions with forest ecosystems shaped by diverse ethnic communities. This linkage aids in assessing farm-forest livelihoods and contributes to climate change mitigation and adaptation decision-making by incorporating experience-based evidence from local and indigenous communities (Dahal et al., 2022). These communities, often referred to as “forest-dependent local stakeholders (FDLS),” are intricately linked with agriculture, livestock husbandry, grazing, pastureland, and forest-dependent goods and services, all within their local cultural context (Acharya et al., 2019; Pandey, 2020a; Pandey et al., 2023; Pandey and Pokhrel, 2021). In this context, it is critical to scrutinize the impact of climate change on local traditions, practices, and ultimately cultural integrity to safeguard them without jeopardizing food security and justice.

Country and region-specific studies on climate change are prevalent worldwide. For instance, in Ethiopia (Debela et al., 2015; Tesfaye and Seifu, 2016), Chile (Roco et al., 2015), Africa (Elum et al., 2017), Switzerland (Shi et al., 2015), Nigeria (Ayanlade et al., 2017), Tanzania (Below et al., 2015), and Romania (Bogdan et al., 2016), among others. In Nepal, numerous scholars have endeavored to assess the perceptions

and understanding of local communities by documenting their experiences and adaptation strategies to climate change across various sectors and locations (Aryal et al., 2016; Devkota et al., 2017; Khanal and Kattel, 2017; Khanal et al., 2018a, b; Mishra et al., 2015; Poudel and Duex, 2017; Shrestha and Aryal, 2011; Sujakhu et al., 2016). However, limited literature focuses on the Terai (lowlands) region in terms of climate change, but this region is recognized as ‘food basket’ of the country and more than half of the country's population resides and has high pressure on balancing the infrastructure needs with food production and residential infrastructure. Previous studies in the lowlands mainly concentrate on flood risk management (Budhathoki et al., 2020; Dulal et al., 2010), agricultural adaptation practices (Chaudhary et al., 2021; Chhetri et al., 2012; Devkota et al., 2017), water shortage, and emergency adaptations (Lamsal et al., 2017; Tiwari et al., 2010) and alterations in plant phenology and forest composition (Shrestha and Shrestha, 2019; Thorn, 2019; Tiwari et al., 2010). Yet, the slow but expanding impact of climate change on customary and cultural practices associated with the livelihood strategies of local and indigenous people amid environmental change remains to be explored, both in policy and practice (Adger et al., 2013).

Further, considering the low-land landscape is crucial because it is not only the ‘food basket’ of Nepal, ensuring over 60 % of the country's food security (NPC, 2024), but also holds significant livelihood and cultural connections with neighboring India in a contiguous landscape (Aryal et al., 2020). Moreover, this landscape hosts a diverse array of forest-dependent local stakeholders (FDLS), including vulnerable indigenous and ethnic communities like Tharu, Musahar, and Chepang (Chaudhary et al., 2021; Thapa, 2019), whose livelihood strategies are particularly sensitive and limited, especially in the face of changing climate conditions (Chaudhary et al., 2022; Piya et al., 2012; Thorn, 2019). These impacts may be further exacerbated if they are not responded to appropriately incorporating knowledge and understanding of indigenous and local communities regarding climate change phenomena (Budhathoki et al., 2020; Lamsal et al., 2017; Nash et al., 2019), and posing significant risks to the affected communities (Dulal et al., 2010; IPCC, 2014; Pandey et al., 2023). In this context, our study aims to address three key questions: (a) What is the current state of observed and perceived climatic experiences among forest-dependent local stakeholders (FDLS) in the lowlands of Nepal? (b) What are the locally differentiated adaptation strategies, considering cultural aspects, across the socio-ecological landscape? (c) What are exemplary cases of how traditional practices, customs, and culture of FDLS have been altered or eroded due to climate change-driven shifts in livelihood strategies in recent decades? Throughout this paper, we recognize indigenous people as those who possess a distinct cultural identity, as enshrined in the Constitution of Nepal (GoN, 2015). We refer to local people as citizens who share the cultural identity and language (Nepali) without having a separate mother tongue, coexisting harmoniously with other than indigenous and ethnic communities (GoN, 2015; NPC, 2024). It's important to note that the primary livelihood strategy of FDLS across the study sites was paddy and maize cultivation. Therefore, in this paper, we use terms such as ‘farmers’, ‘paddy farmers’, ‘local stakeholders’, ‘local communities’, and ‘indigenous and local people’ interchangeably, referring to them collectively as FDLS.

2. Theoretical framework and methods

The research has been framed within the context of the sustainability of the socio-ecological system (SES) (Ostrom, 2009). This approach allows us to examine the interconnectedness of resource systems, resource units, users, and governance systems (institutions) (Anderies et al., 2004; Ostrom and Cox, 2010). Climate change-related actions, spanning from local to international levels, fall within the framework of the United Nations Framework Convention on Climate Change (UNFCCC), necessitating decisions at the international institutional level followed by voluntary adoption at the (sub)national level through national policy

processes. Changes in resource systems prompt users to adopt new strategies, with these user-resource relationships deeply entrenched in local culture over time. The governance of these resources, including carbon services and livelihood strategies reliant on resources, falls under the umbrella of a socio-ecological system, encompassing actions, interactions, and outcomes (Ostrom, 2009, 2007; Ostrom and Cox, 2010). We have tailored the variables of the SES framework to fit the local context, drawing on the standard definitions of ‘indigenous people’ and ‘ethnic communities’ recited in the scholarly literature (Morgan et al., 2009), as well as the localized understanding of these terms enshrined in the constitution of Nepal under Article 51 j(8) (GoN, 2015). Throughout this paper, we use both these terms interchangeably to refer to the same communities.

To meet our study’s goals, we crafted semi-structured questionnaire by customizing variables drawn from previous global studies (Alemagi et al., 2014; Gilani et al., 2017; Tiani et al., 2015; Uisso et al., 2022; Yeang, 2010). These questionnaires were developed in collaboration with a panel of experts and referenced relevant literature while adopting a participatory and resource-conscious approach. We tailored the questionnaires to suit the specific socio-economic conditions of Nepalese participants at the grassroots level. Written in Nepali and translated to the native language as per the necessity concerning the mother tongue of the indigenous communities while administering the interviews, our questionnaire was organized into three main sections: understanding climate change basics, exploring adaptation strategies, and examining the relationship between these strategies and local cultural practices.

In addition to the questionnaire survey, we organized focus group discussions (FGDs) and key informant interviews (KIIs) with local and indigenous communities at selected sites within the district. To ensure both resource availability and methodological simplicity, we opted for oral interviews, aligning with participatory research recommendations (Bürgi et al., 2013) and the methodological strategy from prior studies (Pandey et al., 2023). Our research’s conceptual framework is adopted to capture stakeholders’ experiences and practices in response to

climate-triggered cultural impacts (Fig. 1).

2.1. Study area

The research was conducted in three low-lying districts of Nepal: Chitwan, Saptari, and Jhapa, representing Bagmati, Madhesh, and Koshi Provinces respectively (Fig. 2). These districts are densely populated and play a crucial role in ensuring the food security of the country (NPC, 2024). The Terai region, characterized by lowlands, has the lowest forest coverage compared to other parts of the country. As a result, forest-dependent local stakeholders (FDLS) in this area are experiencing a severe shortage of forest goods and services (DFRS, 2015). Furthermore, the residents in these districts are likely to pose substantial knowledge and awareness regarding climate change and its impacts. This is because numerous governmental and non-governmental organizations have been actively involved in implementing various climate change awareness and support programs in these areas. Additionally, the study region holds three key regional and international advantages. Firstly, it shares a crucial upstream-downstream hydrological linkage between China, Nepal, and India, and extends to the Bay of Bengal. Secondly, the area boasts a similar socio-ecological landscape, fostering transboundary cultural exchange between India and Nepal. Lastly, the region holds international significance in terms of trading and commercial activities.

2.2. Sample design and data collection

This study employed a mixed-methods approach combining both qualitative and quantitative tools and techniques for data collection. This approach offers several advantages, including the ability to comprehensively understand phenomena and delve deeper into underlying factors beyond surface-level observations (Levy, 2005). To gather data, we conducted semi-structured questionnaire interviews with forest dependent local stakeholders (FDLS). Additionally, we conducted

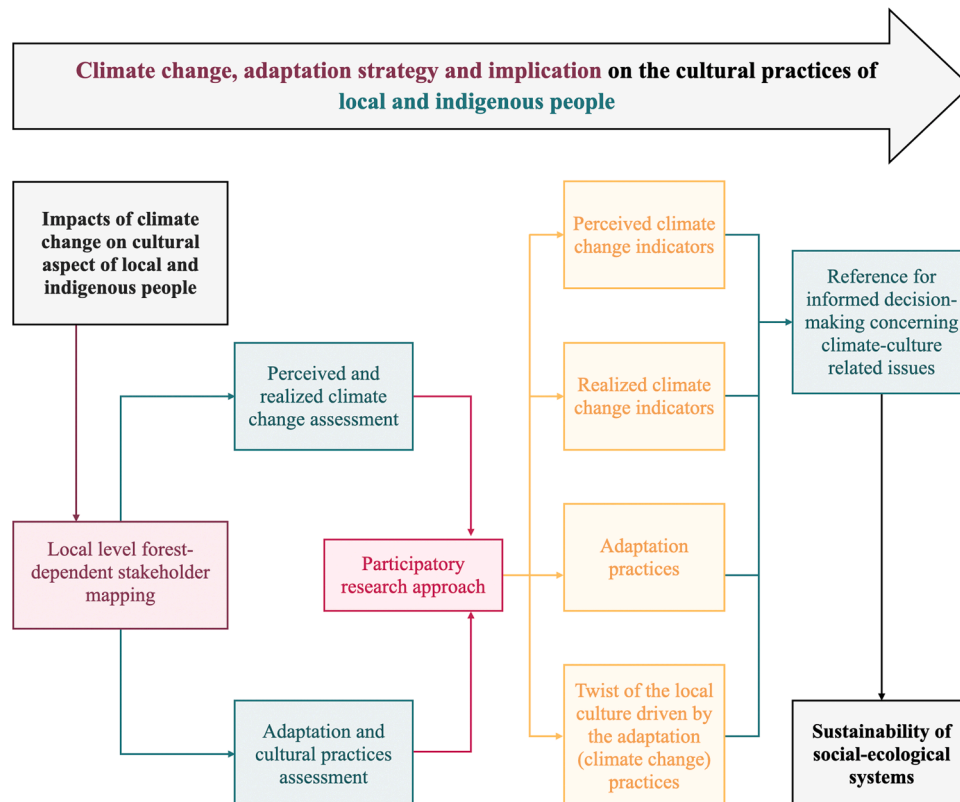


Fig. 1. The conceptual framework of the study and its implications.

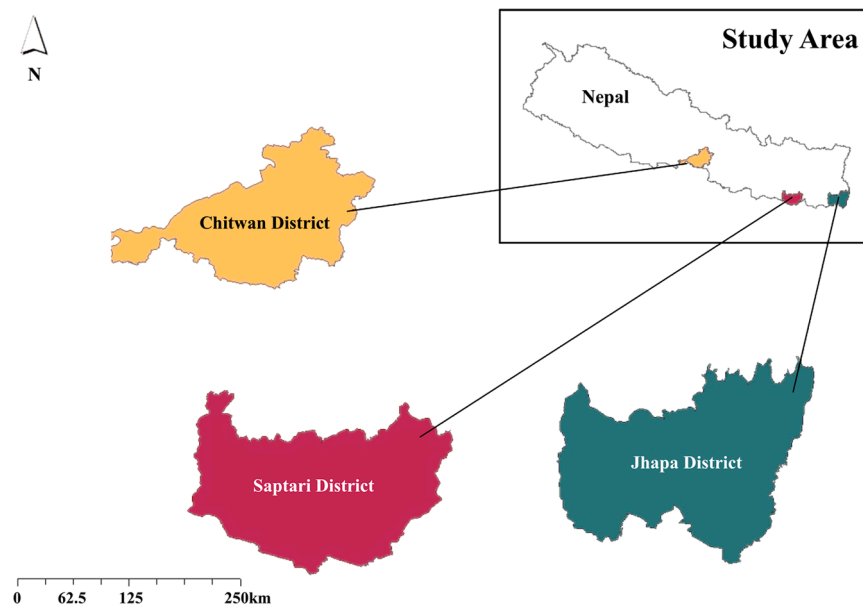


Fig. 2. Map showing the study areas in Nepal along the south and east bordering Indian territory.

transect walks across the landscape, covering both agricultural and forested areas, along with key informant interviews (KIIs) to gather expert viewpoints. Focus group discussions (FGDs) were also held as part of the data collection process. Initially, we organized two-day workshops in each selected district. The participants ($n = 136$) were invited based on specific criteria, including the inclusion of at least 33 % indigenous people, 50 % women, and 33 % individuals from marginalized communities, as outlined in the guidelines for community-based forest management in Nepal (Pandey and Pokhrel, 2021) and most of the members of the Community Forestry Users Group (CFUG) and the focus group discussions are Indigenous people, and therefore, the data reflects their views. We recognize that our approach to participant selection was not entirely random; rather, it was somewhat selective. However, we believe that this selective approach was the most effective way to achieve our desired objectives by adopting the methodology of Pandey et al. (2023).

Participants of the workshop included representatives from various governmental and non-governmental organizations, advocacy groups, and forest user groups, as well as indigenous and hill-migrated farmers (local communities) directly engaged in agriculture and forest-dependent livelihoods across the districts. Additionally, FDLS from rural villages, representing their Community Forest User Groups (CFUGs), were invited to the workshops. This diverse group encompassed individuals of varying ages (22–65 years), genders (45 female, 91 male), ethnic backgrounds (77 indigenous, 59 non-indigenous), and professional roles (48 on-farm, 88 off-farm). Their diverse backgrounds allowed for the collection of a wide range of perspectives on climate change experiences and adaptation strategies specific to their localities, reflecting the socio-cultural diversity of the region. This stakeholder mapping process was conducted under the policy guidelines of Nepal to ensure the inclusion of a representative cross-section of the local community (GoN, 2019; MoFSC/REDD, 2015). During the workshop, the lead researcher explained the study's objectives, the planned methods, and the participants' roles in the information collection process. Participants were briefed about the questionnaire's structure and emphasized the importance of sensitivity in responding to the questions, linkage between indigenous agricultural practices and the food justice, and childhood traditions and current modification in food production and forest services, etc. Each participant was required to provide written ethical consent, confirming that their responses and other information collected would be used solely for research purposes and would be kept

anonymous. This consent process was approved by the ethical committee at the REDD Implementation Centre in Kathmandu, Nepal, following the provisions of the National REDD+ Strategy of Nepal (MoFSC/REDD, 2015).

After the two-day workshops, we trained participants about climate change in the workshop each district, and participants were given a set of semi-structured questionnaires. Local facilitators, who had also attended the workshops, guided the participants through the questionnaires under the lead author's supervision. The questionnaire consisted of 25 questions in Nepali language (see details in *supplementary file_S1*) and were translated into the local languages (e.g., Tharu, Maithali) by the local facilitators if felt necessary. Most questions were objective, allowing participants to choose answers from the provided options, which aimed to make them feel more comfortable. Additionally, a few open-ended questions were included to capture participants' insights, narratives, and ethnographic details on the topic. The questionnaire primarily focused on gathering socio-economic details of the respondents, their perceptions of key climatic variables, perceived impacts of climate change, adaptation practices, and the cultural impacts traditionally associated with responding to perceived climate change.

Following the workshops, a transect walk was conducted in six different localities, comprising two village-forest landscapes in each district, involving FDLS. Led by the lead author, the walk engaged two facilitators alongside indigenous community leaders and farmer-cum-forest user group members. Discussions during the walk covered various topics, including societal dynamics, farming practices, forest management history, and their outcomes. Additionally, participants deliberated on potential causes of observed changes and farmers' strategies concerning cropping, water, and forest management practices. The discussions also delved into cultural and traditional practices of the past, reflecting on participants' childhood memories and noting the gradual changes in customs related to agriculture, water, and forests. These observations provided valuable insights into the evolving landscape of local practices and their implications for climate change adaptation.

Focus group discussions (FGDs) were conducted with specific FDLS, including indigenous communities and occupational groups, totaling nine FGDs (checklist is provided in *supplementary file_S2*). FGDs were organized separately in each district, grouping participants by their profession, ethnic community, and gender, considering their occupational ties to forests. These discussions aimed to explore participants'

general understanding of climate change, their local experiences, and notable changes attributed to climatic phenomena, and validate the responses collected using other tools such as KIIs and field observation. Participants shared insights into their adaptation strategies, whether self-initiated or with external support, and reflected on how climate change and its impacts have influenced their cultural and traditional practices over time in relation to food production and forest goods and services. Additionally, FGDs were conducted with indigenous local community groups, forest user communities, and marginalized local communities, recognizing that climate change impacts and adaptation strategies may vary based on their resilience capacity and traditional cultures. Researchers facilitated the FGDs using semi-structured checklists to guide discussions. In addition to FGDs, key informant interviews (KIIs) were conducted ($n = 27$, nine in each district) to complement the insights obtained from FGDs and semi-structured questionnaire interviews. KIIs involved individuals with expertise and experience relevant to the study objectives. Further, observed climate trend analysis was sourced from the Department of Hydrology and Meteorology, Kathmandu, Nepal (DHM, 2017), providing supplementary evidence to support the findings of the study. These triangulated data sources enriched the study's depth and reliability, contributing to a comprehensive understanding of climate change impacts and adaptation strategies in the study area.

2.3. Data analysis

The collected data underwent analysis using MS Excel, employing a discursive approach, descriptive statistics, and narrative statements. Two methods were utilized for analyzing interview data. Firstly, responses from all participants across the three districts were grouped, as derived from questionnaire interviews. Secondly, narratives and field notes were compiled, synthesizing key insights gathered from FGDs, KIIs and discussions and observations during transect walks. The findings

were compared, discussed, and distilled to extract the core message. Cross-tabulation and Chi-square tests were employed to assess if the frequency of responses for various survey questions varied across districts (Jhapa, Saptari, Chitwan), gender (male and female), profession (primarily agriculture and primarily non-agriculture), and education level (schooling and beyond).

Of the 136 responses, 38 %, 35 %, and 27 % were from Chitwan, Jhapa, and Saptari districts, respectively. Approximately 33 % of all participants were women. Regarding education level, most respondents had completed their schooling, with 29 % having attended university. In terms of occupation, the largest proportion of respondents were farmers (35 %), who were also the primary users of forests. For statistical analysis, only the responses collected through semi-structured questionnaire interviews were considered, and the information collected through FGDs and KIIs was utilized to enrich the results and discussions as appropriate.

3. Results

3.1. Responses on experiencing climate change

The study revealed that FDLS in the lowland landscapes of Nepal has experienced changes in climate, with noticeable shifts in key climatic variables in recent decades (Table 1). Over 85 % of the respondents indicated that they were familiar with climate change before the workshop conducted for the study, with slight variations in response proportions across districts. Specifically, respondents from Chitwan (92.3 %) and Saptari (88.9 %) showed a higher level of awareness regarding the consequences they were facing, compared to those from Jhapa district (75 %). For example, a 54-year-old female respondent from Saptari district expressed:

Table 1

Experiences and perceptions of climate change in the selected district of low land of Nepal by the forest-dependent local stakeholders.

Interview questions and responses	Combined		Chitwan		Jhapa		Saptari	
	Number	%	Number	%	Number	%	Number	%
Have you heard about climate change?								
Yes	116	85.3	48	92.3	36	75	32	88.9
No	20	14.7	4	7.7	12	25	4	11.1
Have you experienced the summer temperature change in later decades compared to your childhood days?								
Increased	112	82.4	44	91.7	36	75	32	88.9
Decreased	12	8.8	–	–	8	16.7	4	11.1
No change	8	5.9	4	8.3	4	8.3	–	–
No idea (missing response)	4	2.9	4	8.3	–	–	–	–
What is your experience with the start of the summer season in later decades compared to your childhood days?								
Start early	100	73.5	40	76.9	28	58.3	32	88.9
Start delay	20	14.7	4	7.7	16	33.3	4	11.1
No change	12	8.8	8	15.4	–	–	–	–
No idea	4	2.9	–	–	4	8.3	–	–
What is your experience with the duration of winter changing in later decades compared to your childhood days?								
Increased	32	23.8	8	15.4	16	33.3	8	22.2
Decreased	88	64.6	36	69.2	24	50.0	28	77.8
No change	12	8.8	4	7.7	–	–	–	–
No idea (missing response)	4	2.9	4	7.7	–	–	–	–
What is your experience with the total amount of annual rainfall that has changed in later decades compared to your childhood days?								
Increased	20	14.7	4	7.7	16	33.3	–	–
Decreased	112	82.4	48	92.3	28	58.3	36	100
No Change	4	2.9	–	–	4	8.3	–	–
No idea	0	0	–	–	–	–	–	–
What is your experience with the timing of the rainfall season (monsoon) changing in later decades compared to your childhood days?								
Early start	8	5.9	–	–	4	8.3	4	11.1
Late start	12	8.8	8	15.4	4	8.3	–	–
Unpredictable	112	82.4	44	84.6	36	75	32	88.9
No change	4	2.9	–	–	4	8.3	–	–
What is your experience with the drought, which changed in later decades compared to your childhood days?								
Increased	124	91.2	48	92.3	40	83.3	36	100
Decreased	8	5.9	–	–	8	16.7	–	–
No idea	4	2.9	4	7.7	–	–	–	–

"We are experiencing prolonged drought in our region nowadays compared to previous decades. These changes have forced us to adjust our paddy cultivation season, as it has become unpredictable. We rely on monsoon rainfall to replenish the water volume in the streams and water canals for irrigation, but the monsoon rainfall has become unpredictable in recent years."

The findings showed that most of the respondents (82.4 %) noted an increase in summer temperatures. Regarding perceived seasonal shifts, 73.5 % of respondents observed that the summer season has commenced earlier in the recent decade compared to earlier decades. However, responses varied significantly across districts, with only 58.3 % of respondents from Jhapa agreeing with this observation, while nearly 90 % of respondents from Saptari confirmed the earlier onset of summer (Table 1).

"I remember working in the fields even during the scorching midday sun, but nowadays, we're confined indoors or seek shelter during daytime hours. Perhaps it's due to aging or rising temperatures. I'm not entirely sure, but conversations in the teashops and under the shade of trees often revolve around climate change and its consequences, such as off-season flooding, the appearance of new pests, and poor maize yields in many areas. I've also noticed a decrease in rainfall compared to my childhood when I used to herd cows," shared a 57-year-old male respondent from the Jhapa district.

Moreover, approximately 65 % of the respondents noted a shortened duration of winter. Concerning changes in the total annual rainfall over the past few decades, nearly 85 % of respondents reported a decrease, with all respondents from the Saptari district in agreement. Additionally, 82.4 % of respondents found the timing of rainfall (monsoon, post-monsoon, winter, pre-monsoon) to be unpredictable in recent decades. Similarly, over 90 % of respondents observed increased drought in later decades (Table 1). Chi-square tests revealed significant differences in knowledge and perceived experiences of climate change across districts and between sexes ($p < 0.05$) but no significant differences were found based on profession or education level ($p > 0.05$) among respondents (Table 2).

3.2. Observed climatic trend

The Department of Hydrology and Meteorology of Nepal maintains comprehensive databases for the country, including the study areas. Analysis of the organization's data reveals observed climatic trends for extreme climate indices (Table 3) that align closely with the experiences reported by the FDLS in the study area (Tables 1 and 2). This is evident by the fact that the significant increase in warm days (Table 3) is complemented by the perceived responses of increased numbers of warm days and reduced winter duration in later decades (Table 1).

Analysis of observed climate indices indicates a notable increase in warm days and a corresponding decrease in cool days and cool nights across the study districts. While the trend is not statistically significant,

Table 2

Chi-square test outputs on the differential experiences of perceived climate change experienced by the FDLS based on the characteristics of the respondents.

Interview question: Have you heard about climate change?			
Variables	Pearson Chi-square value	DF	p-value
District (Chitwan, Jhapa, Saptari)	6.46	2	0.039*
Gender (Male, Female)	4.69	1	0.030*
Profession (Primary agriculture, and primary non-agriculture)	2.61	1	0.106
Education level (up to secondary level (grade 10) and higher than secondary level (higher secondary and university))	0.18	1	0.668

[*Significant at 5 % level of significance].

there has been a decrease in cold spell duration, alongside an increase in consecutive dry days and warm spell duration for the period of 1971–2014 in the study areas (Table 3).

3.3. Impact of climate change experienced by the FDLS

The responses from FDLS underscored their firsthand experience of the tangible impacts of climate change. Findings indicate a notable decrease in crop production, along with increased instances of disease and insect infestation and heightened occurrences of floods and fires. Among the respondents, close to 75 % reported a decrease in crop yield, with slight variations observed across the districts.

"We used to harvest 10 quintals of mustard seed from our field, however, this has decreased to hardly 6 quintals in the past few years, despite our continued efforts," expressed a 62-year-old Tharu woman from Chitwan district.

Nearly 86 % of all respondents concurred that crop diseases and insect infestation have escalated in recent decades compared to earlier periods. The data also revealed that the timing of crop planting and harvesting has become increasingly unpredictable (Table 4).

"Sometimes maize fails to yield any crop, a plight shared by farmers in Bara district as well, as reported by the media. Yet, our struggles remain unheard and unnoticed," lamented a 50-year-old Musahar woman from the Saptari district, speaking in her native Maithili language.

Similarly, the production of potatoes is reported to be reduced or in some years- being destroyed completely by pests and diseases.

"The blight and bleaching diseases, along with red ants, have recurrently ravaged our crops in recent years," expressed another Tharu woman, her frustration evident in her native tongue. "Such occurrences were unheard of in my childhood; if they did happen, they were rare," she added, reflecting on the severity of the situation. "Nowadays, it's increasingly challenging to obtain yields that match the seeds we sow. As a result, we've scaled back our potato cultivation for sale and shifted to growing pulses or leaving the land fallow for some time," she continued. When asked about their adaptation strategies, she explained, "We used to combat red ants with ash and treat bleaching with concentrated mug wort water, but these traditional methods have proven ineffective in recent years." Her husband intervened, his voice tinged with frustration, "We're forced to resort to purchasing pesticides and fungicides from agrochemical stores. These chemicals need to be applied multiple times throughout the season, leading to significant financial losses without any guarantee of increased yields, and lost our traditional agriculture and pest management practices. It's a matter of do or die," he concluded, echoing a popular Hindi proverb.

The impacts of climate change on the forest ecosystem, as perceived by the FDLS, varied both between selected districts and even among respondents within the same district. However, several common trends emerged, including changes in forest structure and species composition, increased pest and disease infestations, more frequent wildfires, heightened presence of alien and invasive species, shifts in phenology, and alterations in the breeding and brooding times of wildlife (see details in supplementary file S3).

"Our houses are surrounded by forests and bushes, built with poor bio-materials and thatched roofs, situated atop remote hills. Fifty years ago, we used to sleep in the forest without any houses. Now we have built houses, but during the dry seasons, we remain awake at night due to the fear of forest fires in recent decades. We have limited access to water to combat the spreading bushfires. In my childhood, the surrounding forest and bushes hardly burned once a decade, and we practiced shifting cultivation. However, in recent decades, the forest burns at least twice and as many as five times in a single year," shared a 65-year-old member of the Chepang community.

Table 3

The observed climatic trends for extreme climate indices of the study areas for the years 1971–2014 [Source: (DHM, 2017)].

District	Rainy days	Consecutive dry days	Consecutive wet days	Very wet days	Extremely wet days	Warm days	Cool days	Warm spell duration	Warm nights	Cool nights	Cold spell duration
Chitwan	0.0	0.1	0.1	0.0	0.0	0.6**	−0.2	0.2	1.0***	−0.3*	0.0
Jhapa	−0.3	0.1	−0.2	0.1	0.0	1.0***	−0.7***	0.1	−0.2	−0.3	−0.1
Saptari	0.1	0.0	0.2	0.0	0.0	0.5*	−0.4*	0.1	0.3	−0.5**	−0.2

[Note: * Statistical significance at 5 %, ** statistical significance at 1 %, and *** statistical significance at 0.1 %. The positive value (+) indicates the increasing trend, and the negative (−) value indicates the decreasing trend of respective climate indices].

Table 4

Perception of respondents on impact and adaptation against climate change.

Understanding climate change impacts	Combined		Chitwan		Jhapa		Saptari	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
What is your experience with crop production changed in later decades compared to your childhood days in your vicinity?								
Increased	12	8.8	4	7.7	4	8.3	4	11.1
Decreased	100	73.5	36	69.2	36	75	28	77.8
No change	12	8.8	8	15.4	0	0	4	11.1
No idea	4	2.9	0	0	4	8.3	0	0
No response	8	5.9	4	7.7	4	8.3	0	0
What is your experience with the crop diseases/insect changes in later decades compared to your childhood days in your vicinity?								
Increased	116	85.9	40	76.9	40	83.4	36	100
No change	4	2.9	4	7.7	0	0	0	0
No idea	4	2.9	4	7.7	0	0	0	0
No response	12	8.8	4	7.7	8	16.7	0	0
What is your experience with the crop planting time changed in later decades compared to your childhood days in your vicinity?								
Early start	20	14.7	4	7.7	8	16.7	8	22.2
Late start	16	11.8	8	15.4	4	8.3	4	11.1
Unpredictable	84	61.8	28	53.8	32	66.7	24	66.7
No change	8	5.9	8	15.4	0	0	0	0
No response	8	5.9	4	7.7	4	8.3	0	0
What is your experience with the frequency of fire events changed in later decades compared to your childhood days in your vicinity?								
Increased	108	79.4	44	84.6	36	75	28	77.8
Decreased	0	0	8	15.4	0	0	0	0
No response	28	20.6	0	0	12	25	8	22.2
No change	0	0	0	0	0	0	0	0
What is your experience with the flood events changed in later decades compared to your childhood days in your vicinity?								
Increasing	108	79.4	44	84.6	36	75	28	77.8
Decreasing	0	0	8	15.4	0	0	0	0
No change	0	0	0	0	0	0	0	0
No response	28	20.6	0	0	12	25	8	22.2
What is your experience with the harvesting time of major crops changed in later decades compared to your childhood days in your vicinity?								
Early start	28	20.6	8	15.4	12	25	8	22.2
Late start	16	11.8	8	15.4	0	0	8	22.2
Unpredictable	68	50	20	38.5	28	58.3	20	55.6
No change	16	11.8	12	23.1	4	8.3	0	0
No response	8	5.9	4	7.7	4	8.3	0	0

Further, FDLS across the study areas reported a reduction in water volume in streams, the drying out of spring water sources and traditional hand pumps, drying marshes and wetlands, frequent flash floods, and the drying of irrigation canals and ponds, based on their experiences.

3.4. Adaptation strategies and cultural disintegration

In response to perceived climate change and its impacts, FDLS has employed various local coping strategies, drawing from both traditional knowledge and recent innovations. One major focus has been on regulating water use for household and agricultural purposes. This involves shifting from conventional to more adaptive and modified crop varieties, as well as adjusting management practices from culturally driven traditional methods to market-driven, imported, and non-eco-friendly mechanized approaches aimed at climate resilience. For instance, there's been a transition to hybrid maize and paddy instead of relying solely on traditional local varieties. Similarly, there's been a shift towards mechanical plowing, replacing traditional methods using oxen or he-buffaloes. Additionally, there's been a reduction in the size of livestock herds, resulting in less cattle dung and farmyard manure for fertilizing fields, with a preference for organic fertilizers instead.

However, these adaptations have also weakened the traditional farm-forest linkages. This reduction in reliance on forests has impacted various ecosystem services, such as providing fodder and bedding materials, wood, and fuelwood. It has also affected indirect ecosystem services, like habitat provision for wildlife, including birds and insects crucial for supporting agricultural systems through processes such as pollination and maintaining food web balance. These intricate relationships are deeply rooted in the unique local culture of the communities.

"We have had to make significant changes in our cropping patterns due to the decrease in water sources and average annual rainfall over the years. Instead of cultivating paddy throughout our lands as we used to, we have shifted to growing sugarcane and tobacco, which require less water," explained a 60-year-old man from the Musahar ethnic community in Saptari district.

"Chiuri (Diploknema butyracea) trees, which are culturally significant to us Chepang community as they are traditionally given as dowry to the bride, have been giving us trouble in recent decades. The production has decreased, and the fruiting cycle has become irregular, with longer gaps between fruitful years due to changing environmental phenomena

(climate change). Normally, these trees used to yield well every other year, but now the situation has changed. This decline has led to limited regeneration, reduced honey, and butter production, and threatens the continuity of our cultural practices. It's becoming increasingly difficult to uphold our cultural traditions, especially for people like me with five daughters. We feel pressured to abandon our customs due to these challenges. Unfortunately, despite efforts from various organizations coming to our village, none seem to understand or address this issue, which is deeply distressing for us," expressed a 59-year-old Chepang man from Chitwan district, visibly emotional.

FDLS in the study areas has implemented various strategies to address the drying of water sources and sustain agriculture systems amidst climate change. These include deepening bore wells, increasing the use of motor pumps, leaving land fallow, advocating for mass irrigation facilities, adopting rainwater harvesting, utilizing wastewater for irrigation, implementing drip irrigation, and switching to more adaptive, less water-intensive crop varieties. Additionally, they have shifted from traditional crops like paddy and wheat to alternatives such as sugarcane and tobacco. However, the drying of drinking water sources has led to an increase in daily water fetching time, ranging from 0.5 to 2 h.

"We used to fish in the surrounding wetlands near our paddy fields, just like my father and grandfather did. But now, those wetlands are drying out, and many have disappeared entirely. Our children don't even know how to swim or fish because there's no water, and consequently, no fish. Additionally, we used to own and operate water mills for grinding grains, but now there's no water to power them. All the streams have dried up and the water-based traditions are being lost, a 63-year-old Tharu women recall her past from the Chitwan district."

These changes result in a severe water shortage, affecting agriculture and water-dependent livelihoods like water mills and fishing. Livestock husbandry and forest-related activities are also impacted. These findings suggest that climate change is gradually eroding cultural integrity for agriculture production and sustaining livelihood strategies of indigenous and local communities and imposing additional burdens on livelihood management for FDLS in Nepal's lowland region.

4. Discussion

The study investigates the impacts of climate change on forest-dependent livelihood and adaptation strategies in the lowlands of Nepal, aiming to navigate their implications to the cultural practices and traditional customs of local and indigenous people. Significant changes in climatic variables, particularly temperature and rainfall, have been observed, supported by meteorological data and local perceptions. These changes include a decrease in cool nights and days, an increase in warm days, dry spells, and warm spells, and a decrease in cold spells, leading to acute water shortages affecting agriculture, water-based livelihoods, livestock husbandry, and forest resources. In response, the forest-dependent local stakeholders (FDLS) have adopted new strategies, though these often replace traditional practices, eroding local traditions and customs. Increased summer temperatures decreased annual rainfall, unpredictable rainfall patterns, increased drought, and an early onset of summer have impacted agricultural productivity, leading to increased pest infestations and water shortages, and contributing to food insecurity. Adaptive strategies include crop diversification, changing planting schedules, and engaging in non-farming activities, but these require advanced technology and investment, posing challenges to sustaining traditional agricultural practices. Climate change has also led to significant changes in water management and forest ecosystem services, impacting livelihoods and cultural practices. Therefore, the study emphasizes that urgent policy decisions are needed to safeguard local and indigenous cultural integrity and secure livelihoods in the face of global environmental changes.

4.1. Temperature change and adaptation strategies

The results indicate significant changes in climatic variables, particularly temperature and rainfall, in the lowlands of Nepal. These findings are supported by data from meteorological stations and local perceptions in the selected districts. We observed a decrease in cool nights and days, an increase in warm days, consecutive dry days, and warm spell duration, and a decrease in cold spell duration, suggesting warming in the Terai region. These changes have led to an acute water shortage, affecting agriculture and water-based livelihoods such as water mills and fishing, as well as their interconnected relationship with livestock husbandry and forest resources. In response to these shifting climatic patterns in Nepal's agricultural hub, FDLS have adopted new strategies to cope with the changing circumstances and sustain their livelihoods. Similar observations of perceived climate changes and their adverse impacts on various ecosystem aspects and livelihood options have been reported elsewhere (Ranjitkar et al., 2016; Shrestha et al., 2019), including in the lowlands (Pandey et al., 2023; Thorn, 2019; Tiwari et al., 2010). Consequently, FDLS, including marginalized and vulnerable indigenous communities like the Chepang, Musahar, and Tharu, across the lowlands, face significant pressure to sustain their livelihoods and cultural practices (Adger et al., 2013). Despite this pressure, climate change adaptation strategies are seen as necessary and inevitable. As a result, FDLS is adopting locally available and market-driven adaptation strategies. However, locally adopted strategies did not last long whereas market-driven approaches not only increase the cost of livelihoods but also require high-tech knowledge and skills. Consequently, these processes have gradually replacing traditional practices and skills, eroding local traditions and cultures (Magni, 2017). Given that the transfer of indigenous knowledge, skills, and practices across generations takes a significant amount of time (Ifejika Speranza et al., 2010), urgent policy decisions and affirmative actions are needed to safeguard local and Indigenous cultural integrity and secure livelihoods in the face of global environmental changes.

Most respondents perceive increased summer temperatures, decreased annual rainfall, unpredictable rainfall patterns, increased drought, and an early onset of summer. These changes directly impact agricultural production and productivity, which form the basis of livelihood strategies for FDLS. The increased infestation of pests and diseases, acute water shortages, changing rainfall patterns (for rain-fed agriculture), and increased flash floods contribute to the decline in agricultural production. These observations align with findings from other studies conducted in Nepal (Khanal and Kattel, 2017; Mishra et al., 2015; Paudel et al., 2020). The heightened impacts of climate change on agriculture in this region are likely to exacerbate the food security situation nationwide. Although studies, including strategic documents such as the national adaptation plan and action, followed by national adaptation plans, have highlighted the vulnerability of food production in Nepal's lowlands to climate change (NAPA, 2010; Shrestha et al., 2019), affirmative policy decisions are yet to be made to ensure local food security. These decisions should encompass culturally guided practices such as the 'barter' system, conservation of indigenous varieties, cultivation of local breeds, and cross-border food trade, both voluntary and commercial, to mitigate the effects of climate change on the food production system.

In response to the perceived adverse effects of climate change, FDLS employs diverse adaptive strategies. Notable responses include switching crop varieties, adjustments to planting and harvesting schedules, and engagement in non-farming activities to sustain livelihoods. Previous studies also document strategies such as changing rice varieties, improving irrigation management, altering cropping patterns, and constructing terraces to enhance livelihood security in the face of perceived climate change (Khanal and Kattel, 2017; Thorn, 2019; Tiwari et al., 2010). The adoption of drought-tolerant varieties is a common climate response strategy noted by some scholars (Dulal et al., 2010; Elum et al., 2017). However, others argue that changes in crop varieties

and cropping patterns in Nepal are influenced more by technological and market-related factors than by responses to climate change (Budhathoki and Zander, 2020). Nevertheless, some scholars strongly assert that selecting drought-resistant and high-yielding varieties can boost crop production in response to climate change, prompting local adoption (Chaudhary et al., 2021; Khanal et al., 2018a; Thorn, 2019). However, the preference for drought-resistant crop varieties poses a threat to maintaining agro-biodiversity, as local varieties may disappear. In this study, FDLS from Chitwan district reported a decrease in mustard (*Brassica rapa*) cultivation due to declining yields in recent decades, attributed to changes in climatic variables. This suggests that climate change poses a silent risk to the socio-economy and future livelihoods of local people reliant on indigenous species (Aryal et al., 2020; Debela et al., 2015). Moreover, such adaptive strategies not only increase the financial and time burdens or require advanced technology for management but also exert pressure to displace local varieties and disrupt the culture of seed preservation and cultivation at the household level, developed through generations of experimentation and practice. This presents another serious concern for policy decisions regarding climate actions, from local to global levels.

4.2. Climate-triggered water shortage and adaptation strategies

We found that FDLS now spends more time on water management due to the drying up of water sources, a stark contrast to previous decades. They are gradually switching to low-water crops, a trend observed in past regional studies (Poudel and Duex, 2017; Thorn, 2019). These changes directly impact overall food production and discourage farmers from continuing their agricultural efforts due to uncertainties regarding new varieties, cultivation techniques, and market conditions (Chhetri et al., 2012). Moreover, there is increasing evidence of high input but low output in traditional production systems (Chaudhary et al., 2021), leading to disillusionment among the younger generations towards agriculture (Devkota et al., 2018; Joshi et al., 2014). Consequently, traditional agricultural systems and their associated knowledge, skills, and practices are discontinuing across generations, resulting in cultural erosion deeply intertwined with livelihood strategies dating back generations. Further, respondents from the Saptari district emphasized that the drying out of tube wells in recent decades has made it difficult to attract brides to their area. Studies have also highlighted increased crop and livestock diseases and rising food prices, affecting food security for smallholder farmers due to acute water shortages in the agriculture sector in Nepal (Lamsal et al., 2017; Vaidya and Sharma, 2014). Similar observations have been reported in Ethiopia (Tesfaye and Seifu, 2016). The severity of these impacts may stem from poor resilience capacity (Piya et al., 2012) and limited water infrastructure facilities in countries like Nepal (NPC, 2024). Therefore, investments are needed in conserving traditional water management practices and developing the resilience capacity of communities, recognizing water as a critical resource for sustainable horizons.

We found that FDLS adopted various water conservation strategies, including rainwater harvesting, construction of water ponds, reducing reliance on spring water sources, collecting water in tanks, pipelining water sources to minimize leakage and wastage, and deepening existing water wells. However, these strategies may have long-term implications, such as a severe decline in the groundwater table due to imbalances in recharge and extraction (Tiwari et al., 2010). Moreover, they often require higher costs and technologies, adding additional burdens to water management (Dulal et al., 2010; Pandey et al., 2023). Although rainwater is the primary source of groundwater recharge (Gemeda et al., 2021; Shahzad et al., 2019), precipitation patterns have shown a declining trend or become unpredictable, indicating the lesser amount available for adding the water volume to water sources. This poses challenges for sustaining water resources in the low-lands region of the country, where groundwater is the main water source for household use and irrigation in the farmland. Most of the adopted strategies may deem

unsustainable due to strategic geomorphological characteristics, such as those found across the Chure range (MoFE, 2019; NAPA, 2010; Pandey, 2003), compounded by multiple drivers of ecosystem degradation and the impact of climate change (Pandey et al., 2022) through minimal groundwater recharge and increased flood risk, high silt and sediment loads in the stream (Bogdan et al., 2016) and decrease in the groundwater table to meet the pumping out for domestic and non-domestic uses (Boissière et al., 2013) leading to further degradation of the lands. Consequently, land degradation further exacerbates degrading land quality, reducing agriculture production, and posing challenges to drinking water availability and ecosystem health (Pandey, 2020b; Pandey, 2017, 2011). We observed changes in the livelihoods of water-dependent communities, such as Tharu, whose fishing traditions have been impacted. Sensitizing stakeholders to affirmative alternatives (Kais and Islam, 2019) and implementing locally-driven, long-term water management strategies that preserve the cultural integrity of indigenous people is necessary. These actions also will be crucial for combating land degradation and achieving commitments outlined in international conventions and land degradation neutrality such as the United Nations Convention to Combat Desertification.

4.3. Climate-driven agriculture and forest ecosystem services

We also highlight changes in site- and community-specific relationships with agriculture- and forest-ecosystem goods and services driven by climate change in recent decades compared to traditional practices (see details in *supplementary file S3*). One notable example is the modification of cropping patterns and diversified crop rotation strategies adapted by FDLS in the Terai region of Nepal. While diversified cropping systems have been reported to address many challenges posed by changing climatic variables (Shah et al., 2021), all approaches are not universally applicable across all locations and cultural contexts (Adger et al., 2013; Tiwari et al., 2010). For instance, during group discussions, some participants mentioned shifting from aquaculture to paddy farming, paddy farming to sugarcane cultivation, and subsequently to tobacco farming due to water scarcity, especially in the Saptari district. They believed that these alternative strategies were less water intensive. However, such coping mechanisms may have socio-economic and psychological implications. For example, sugarcane farming has become less profitable for farmers due to reduced production and inadequate returns from sales to sugar mill owners (Neupane et al., 2017). This has severely impacted food security, particularly rice and fish production (Neupane et al., 2017). Moreover, farmers often face challenges in reclaiming sugarcane fields for regular cereal crops due to the high financial investment required. Similar experiences have been reported in the tobacco industry in Nepal (Bhatta et al., 2020; Khanal and Khatri, 2021). Addressing this turmoil requires a strong and cooperative government with regulatory policies, support for the private sector, and compliant citizens to achieve prosperity and sustainable landscapes.

The FDLS in the study areas has reported several significant indicators of changes in the forest ecosystem. These include increased deforestation and degradation, alterations in structure and cover, rising infestation of diseases and invasive alien species, and heightened occurrences of wildfires, bushfires, and forest fires. Such fires directly impact soil moisture, seed germination, and the micro-ecology of forests, leading to shifts in forest composition and structure (Kobziar et al., 2022; Neeraja et al., 2021). These changes have distinct effects on the socio-ecological landscape, influencing adaptations and behavioral responses related to forest ecosystem services (Howe et al., 2013; Zheng and Dallimer, 2016). For instance, the proliferation of invasive species results in biodiversity loss, impacting the livelihoods, economies, and ecosystem services (Shrestha and Shrestha, 2019). As the relationship between people and forest ecosystems changes due to climate change, socio-economic and eco-cultural relationships also diverge (Adger et al., 2013; Gentle et al., 2014). Consequently, the traditional practices, knowledge, skills, attitudes, and arts of forest-dependent communities,

which have been established over time, may vanish. The extent and magnitude of climate change impacts can directly influence people's perceptions, ultimately determining the degree of cultural loss (Weber, 2010). Given the severity of climate change impacts on FDLS, the likelihood of gradual culture disintegration is evident. In this context, timely responses in conserving traditional customary practices and ethnobotanical knowledge of FDLS are imperative (Aryal et al., 2023c). Tangible affirmative decisions and actions are necessary to conserve local culture and address changing environmental phenomena through effective, efficient, and participatory approaches (Yeh et al., 2014).

FDLS in the study areas noted behavioral changes in wildlife patterns attributed to climate change. For instance, respondents have observed increased visits by wild animals like blue bull (*Boselaphus tragocamelus*) to households' water-pond in search of water, a phenomenon previously uncommon. This shift may stem from the drying of natural water sources in their habitats, underscoring the urgency of strategic wildlife and ecosystem management to address climate change-induced challenges. Additionally, habitat fragmentation could contribute to the synchronization of wildlife movements, further impacting their behavior and distribution (Acharya et al., 2017) and disruption of natural populations, governed by self-regulating systems such as the food web and predator-prey relationships, poses a challenge (Pandey et al., 2023). *'Such incidents exacerbate negative interactions between humans and wildlife, posing risks for both parties, as reported by the key informants.'* To overcome this challenge, strategies should focus on sustainable wildlife and habitat management, and proper land-use planning (Maraseni et al., 2022), enhancing livelihood options, and reducing dependency on forests by creating alternative opportunities for indigenous and local people (Pandey, 2020a). Such strategies could promote coexistence and ensure the safety of both human and non-human species, contributing to species justice as well as social welfare in the face of climate change (Porter et al., 2020; Schlosberg and Collins, 2014).

Overall, the study delves into the perceived impacts of global environmental changes at the local level and the adaptation strategies of FDLS in the low-land social-ecological landscape of Nepal. By presenting case-specific examples, we shed light on the impacts of climate change on agriculture and forest ecosystems, emphasizing their implications for social and ecological sustainability. Additionally, we examine the multifaceted negative impact of water scarcity on food security and the forest ecosystem, which has become increasingly acute in recent years. A unique aspect of our study is the exploration of cultural disintegration caused by climate change, highlighting the need for policy decisions to address this overlooked dimension. However, it is important to note that our study lacks spatial and temporal data on climate change variability and its connection to stakeholder culture, as well as quantification of the impacts and various dimensions of adaptation strategies related to local culture. Further, we could not cover all aspects of climate change, associated factors like technological and developmental changes, and globalization impacts, and include all categories of stakeholders and indigenous groups, leaving room for future research. We acknowledge the limitation of solely relying on a small number of respondents. A larger sample size, covering a wide range of geographic areas would offer better representation and more robust support of claims and is suggested for further study. Nevertheless, our study offers valuable insights into local-level climate change experiences of deeply rooted cultural FDLS, its impacts on food production and forest ecosystems, and locally driven adaptation strategies, are replicable to the other similar socio-economic contexts of Nepal and beyond. By isolating the impact of climate change on the cultural aspects of local and indigenous communities on food security and justice, we contribute a novel perspective to the existing climate change literature. Our findings serve as solid evidence for policy decisions aimed at sustainable management of food production and forest ecosystems in the face of global climate change, while also safeguarding the cultural integrity of indigenous and local communities. Findings support efforts to achieve sustainable development goals (UN, 2015) and climate action without compromising food

security, biodiversity conservation, or cultural integrity at the national level (NPC, 2017), in particular, and without jeopardizing food justice and biodiversity conservation globally (Pandey et al., 2024a; Pandit et al., 2021).

5. Conclusion and future pathways

Climate change and its impacts are evident both globally and locally. This study explores a unique aspect of climate change's effect on cultural integrity in relation to sustainable agrifood production systems among forest-dependent indigenous and local communities, particularly in the low-lying landscapes of Nepal. Our findings indicate that both the perceptions of forest-dependent local stakeholders (FDLS) and meteorological data reveal significant climatic changes over recent decades. These shifts have forced local communities to adopt new livelihood strategies. However, some of these strategies introduce financial and technological burdens, unintentionally eroding local culture, customs, traditional knowledge, practices, and skills. This rapid and irreversible loss poses a serious threat to community well-being and sustainable landscapes. Therefore, future policies must prioritize preserving indigenous and local cultural traditions within food production systems amid global environmental changes and ongoing developments.

Furthermore, our findings and discussions suggest potential pathways for both short- and long-term actions. These include providing subsidies to FDLS to offset production losses and conserve local species in alignment with climate agreements, implementing insurance mechanisms for climate-related losses, improving sustainable water and forest management, investing in research on climate-resilient crop varieties, promoting human-wildlife coexistence for safety, and managing invasive species sustainably. The loss of cultural integrity tied to the livelihood strategies of local and indigenous communities is intangible and irreversible, demanding urgent attention from policymakers and practitioners. Our findings provide insights for informed decision-making to uphold socio-cultural justice and landscape sustainability amid global environmental changes. Equitable actions should extend beyond resource access to include economic opportunities, cultural preservation, and inclusive policy development for a sustainable future.

Data availability

The data will be available upon request from the corresponding author.

Ethical approval

Authors adhere to the publishing ethic and approve as per the ethical guidelines of the journal.

Consent to participate

The authors informed the participants/respondents pre-prior and got consent on the data acquisition and use of information during the data collection, and all the participants have approved the consent to participate as per their will verbally.

Consent to publish

Authors were informed of the participants/respondents prior to publication and got consent on the publication of the information provided by them anonymously.

CRediT authorship contribution statement

Hari Prasad Pandey: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Suman Aryal:** Writing – review & editing,

Writing – original draft, Visualization, Methodology. **Bishnu Hari Poudyal**: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation. **Shreejana Bhusal**: Writing – review & editing, Writing – original draft, Methodology, Data curation. **Tek Narayan Maraseni**: Writing – review & editing, Validation, Supervision.

Declaration of competing interests

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

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Supplementary materials

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References

- Acharya, K.P., Paudel, P.K., Jnawali, S.R., Neupane, P.R., Köhl, M., 2017. Can forest fragmentation and configuration work as indicators of human-wildlife conflict? Evidences from human death and injury by wildlife attacks in Nepal. *Ecol. Indic.* 80, 74–83. <https://doi.org/10.1016/j.ecolind.2017.04.037>.
- Acharya, R.P., Maraseni, T., Cockfield, G., 2019. Global trend of forest ecosystem services valuation – an analysis of publications. *Ecosyst. Serv.* 39, 100979. <https://doi.org/10.1016/j.ecoser.2019.100979>.
- Adger, W.N., Barnett, J., Brown, K., Marshall, N., O'Brien, K., 2013. Cultural dimensions of climate change impacts and adaptation. *Nat. Clim. Change* 3, 112–117. <https://doi.org/10.1038/nclimate1666>.
- Alemagi, D., Minang, P.A., Feudjio, M., Duguma, L., 2014. REDD+ readiness process in Cameroon: an analysis of multi-stakeholder perspectives. *Clim. Policy* 14, 709–733. <https://doi.org/10.1080/14693062.2014.905439>.
- Anderies, J.M., Janssen, M.A., Ostrom, E., 2004. A framework to analyze the robustness of social-ecological systems from an institutional perspective. *Ecol. Soc.* 9.
- Aryal, J.P., Sapkota, T.B., Khurana, R., Khatri-Chhetri, A., Rahut, D.B., Jat, M.L., 2020. Climate change and agriculture in South Asia: adaptation options in smallholder production systems. *Environ. Dev. Sustain.* 22, 5045–5075. <https://doi.org/10.1007/s10668-019-00414-4>.
- Aryal, K., Maraseni, T., Apan, A., 2023a. Transforming agroforestry in contested landscapes: a win-win solution to trade-offs in ecosystem services in Nepal. *Sci. Total Environ.* 857, 159301. <https://doi.org/10.1016/j.scitotenv.2022.159301>.
- Aryal, K., Maraseni, T., Apan, A., 2023b. Understanding production possibility frontiers and utility values of ecosystem services in the Himalayas: an analysis of the supply-demand divide. *J. Clean. Prod.* 423, 138725. <https://doi.org/10.1016/j.jclepro.2023.138725>.
- Aryal, K., Maraseni, T., Apan, A., 2023c. A call for 'management authorship' in community forestry. *Environ. Sci. Policy* 139, 204–208. <https://doi.org/10.1016/j.envsci.2022.10.023>.
- Aryal, S., Cockfield, G., Maraseni, T.N., 2016. Perceived changes in climatic variables and impacts on the transhumance system in the Himalayas. *Clim. Dev.* 8, 435–446. <https://doi.org/10.1080/17565529.2015.1040718>.
- Ayanlade, A., Radeny, M., Morton, J.F., 2017. Comparing smallholder farmers' perception of climate change with meteorological data: a case study from southwestern Nigeria. *Weather Clim. Extrem.* 15, 24–33. <https://doi.org/10.1016/j.wace.2016.12.001>.
- Below, T.B., Schmid, J.C., Sieber, S., 2015. Farmers' knowledge and perception of climatic risks and options for climate change adaptation: a case study from two Tanzanian villages. *Reg. Environ. Change* 15, 1169–1180. <https://doi.org/10.1007/s10113-014-0620-1>.
- Bhatta, D.N., Crosbie, E., Bialous, S.A., Glantz, S., 2020. Defending comprehensive tobacco control policy implementation in Nepal from tobacco industry interference (2011–2018). *Nicot. Tobacco Res.* 22, 2203–2212. <https://doi.org/10.1093/ntnr/ntaa067>.
- Bogdan, S.-M., Pătru-Stupariu, I., Zaharia, L., 2016. The assessment of regulatory ecosystem services: the case of the sediment retention service in a mountain landscape in the southern romanian carpathians. *Proc. Environ. Sci. ECOSMART* - Environ. Crossroads: Smart Approach. *Sustain. Develop.* 32, 12–27. <https://doi.org/10.1016/j.proenv.2016.03.008>.
- Boissière, M., Locatelli, B., Sheil, D., Padmanaba, M., Sadjudin, E., 2013. Local perceptions of climate variability and change in tropical forests of Papua, Indonesia. *Ecol. Soc.* 18. <https://doi.org/10.5751/ES-05822-180413>.
- Budhathoki, N.K., Paton, D., Lassa, J.A., Zander, K.K., 2020. Assessing farmers' preparedness to cope with the impacts of multiple climate change-related hazards in the Terai lowlands of Nepal. *Int. J. Dis. Risk Reduct.* 49, 101656. <https://doi.org/10.1016/j.ijdr.2020.101656>.
- Budhathoki, N.K., Zander, K.K., 2020. Nepalese farmers' climate change perceptions, reality and farming strategies. *Clim. Dev.* 12, 204–215. <https://doi.org/10.1080/17565529.2019.1612317>.
- Bürgi, M., Gimmi, U., Stuber, M., 2013. Assessing traditional knowledge on forest uses to understand forest ecosystem dynamics. *For. Ecol. Manage.* 289, 115–122. <https://doi.org/10.1016/j.foreco.2012.10.012>.
- Chaudhary, A.K., Pandit, R., Burton, M., 2022. Farmyard manure use and adoption of agricultural mechanization among smallholders in the Mahottari District, Nepal. *World Dev. Perspect.* 25.
- Chaudhary, B.R., Acciaioli, G., Erskine, W., Chaudhary, P., 2021. Responses of the Tharu to climate change-related hazards in the water sector: indigenous perceptions, vulnerability and adaptations in the western Terai of Nepal. *Clim. Dev.* 13, 816–829. <https://doi.org/10.1080/17565529.2021.1889947>.
- Chhetri, N., Chaudhary, P., Tiwari, P.R., Yadaw, R.B., 2012. Institutional and technological innovation: understanding agricultural adaptation to climate change in Nepal. *Appl. Geogr. Health Imp. Glob. Clim. Change: Geogr. Perspec.* 33, 142–150. <https://doi.org/10.1016/j.apgeog.2011.10.006>.
- Clayton, S., Devine-Wright, P., Stern, P.C., Whitmarsh, L., Carrico, A., Steg, L., Swim, J., Bonnes, M., 2015. Psychological research and global climate change. *Nat. Clim. Change* 5, 640–646. <https://doi.org/10.1038/nclimate2622>.
- Dahal, G., Malla, Y., Pokharel, B., Khanal, D., Gentle, P., Paudel, H., 2022. Community forestry policy and legal framework. In: Paudel, N.S., Ojha, H., Banjade, M.R., Karki, R., Tamang, S. (Eds.), *Revitalising Community Forestry in the Changing Socioeconomic Context of Nepal. EnLIFT2 programme and Forest Action Nepal, Kathmandu*.
- Debelal, N., Mohammed, C., Bridle, K., Corkrey, R., McNeil, D., 2015. Perception of climate change and its impact by smallholders in pastoral/agropastoral systems of Borana, South Ethiopia. *Springerplus*. 4, 236. <https://doi.org/10.1186/s40064-015-1012-9>.
- Devkota, N., Phuyal, R., Shrestha, D., 2018. Cost and benefit analysis of adoption of climate change adaptation options among rural rice farmers in Nepal. *Asian J. Agric. Rural Develop.* 7, 136–148. <https://doi.org/10.18488/journal.1005/2017.7.7/1005.7.136.148>.
- Devkota, R.P., Pandey, V.P., Bhattarai, U., Shrestha, H., Adhikari, S., Dulal, K.N., 2017. Climate change and adaptation strategies in Budhi Gandaki River Basin, Nepal: a perception-based analysis. *Clim. Change* 140, 195–208. <https://doi.org/10.1007/s10584-016-1836-5>.
- DFRS, 2015. *State of Nepal's forests*. Department of Forest Research and Survey, Kathmandu, Nepal.
- DHM, 2017. Observed climate trend analysis in the districts and physiographic region of Nepal (1971–2014).
- Dulal, H.B., Brodnig, G., Thakur, H.K., Green-Onoriose, C., 2010. Do the poor have what they need to adapt to climate change? A case study of Nepal. *Local Environ.* 15, 621–635. <https://doi.org/10.1080/13549839.2010.498814>.
- Eckstein, D., Wings, M., Künzel, V., Schäfer, L., Germanwatch, 2019. Global climate risk index 2020 who suffers most from extreme weather events? Wether-related loss events in 2018 and 1999 to 2018.
- Elum, Z.A., Modise, D.M., Marr, A., 2017. Farmer's perception of climate change and responsive strategies in three selected provinces of South Africa. *Clim. Risk Manage.* 16, 246–257. <https://doi.org/10.1016/j.crm.2016.11.001>.
- Gemeda, D.O., Feyssa, D.H., Garedew, W., 2021. Meteorological data trend analysis and local community perception towards climate change: a case study of Jimma City, Southwestern Ethiopia. *Environ. Dev. Sustain.* 23, 5885–5903. <https://doi.org/10.1007/s10668-020-00851-6>.
- Gentle, P., Thwaites, R., Race, D., Alexander, K., 2014. Differential impacts of climate change on communities in the middle hills region of Nepal. *Nat. Hazards* 74, 815–836. <https://doi.org/10.1007/s10669-014-1218-0>.
- Gilani, H.R., Yoshida, T., Innes, J.L., 2017. A collaborative forest management user group's perceptions and expectations on REDD+ in Nepal. *For. Policy Econ.* 80, 27–33. <https://doi.org/10.1016/j.forpol.2017.03.004>.
- GoN, 2019. National climate policy 2019.
- GoN, 2015. Constitution of Nepal (2015).
- Hamilton, L.C., Keim, B.D., 2009. Regional variation in perceptions about climate change. *Int. J. Climatol.* 29, 2348–2352. <https://doi.org/10.1002/joc.1930>.
- Howe, P.D., Markowitz, E.M., Lee, T.M., Ko, C.Y., Leiserowitz, A., 2013. Global perceptions of local temperature change. *Nat. Clim. Change*.
- Ifejika Speranza, C., Kitenge, B., Ambenje, P., Wiesmann, U., Makali, S., 2010. Indigenous knowledge related to climate variability and change: insights from droughts in semi-arid areas of former Makueni District, Kenya. *Clim. Change* 100, 295–315. <https://doi.org/10.1007/s10584-009-9713-0>.
- IPCC, 2021. Summary for policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New

- York, NY, USA. Cambridge University Press, pp. 3–32. <https://doi.org/10.1017/9781009157896.001>.
- IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability - contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change | environmental migration portal [WWW Document]. URL <http://environmentalmigration.iom.int/climate-change-2014-impacts-adaptation-and-vulnerability-contribution-working-group-ii-fifth> (accessed 10.15.20).
- Ives, J.D., Messerli, B., Messerli, B., 2003. The Himalayan Dilemma : Reconciling Development and Conservation. Routledge. <https://doi.org/10.4324/9780203169193>.
- Joshi, K.D., Khanal, N.P., Harris, D., Khanal, N.N., Sapkota, A., Khadka, K., Darai, R., Neupane, R.K., Joshi, M., Witcombe, J.R., 2014. Regulatory reform of seed systems: benefits and impacts from a Mungbean case study in Nepal. *Field Crops Res.* 158, 15–23. <https://doi.org/10.1016/j.fcr.2013.12.011>.
- Kais, S.M., Islam, M.S., 2019. Perception of climate change in shrimp-farming communities in Bangladesh: a critical assessment. *Int. J. Environ. Res. Public Health* 16, 672. <https://doi.org/10.3390/ijerph16040672>.
- Khanal, G.N., Khatri, R.B., 2021. Burden, prevention and control of tobacco consumption in Nepal: a narrative review of existing evidence. *Int. Health* 13, 110–121. <https://doi.org/10.1093/inthealth/ihaa055>.
- Khanal, S., Kattel, R.R., 2017. Understanding farmers' perceptions and adaptations to climate change and variability in rice production at the Kaski and Chitwan districts, Nepal. *Asian Res. J. Agric.* 1–12. <https://doi.org/10.9734/ARJA/2017/29761>.
- Khanal, U., Wilson, C., Hoang, V.-N., Lee, B., 2018a. Farmers' adaptation to climate change, its determinants and impacts on rice yield in Nepal. *Ecol. Econ.* 144, 139–147. <https://doi.org/10.1016/j.ecolecon.2017.08.006>.
- Khanal, U., Wilson, C., Lee, B.L., Hoang, V.-N., 2018b. Climate change adaptation strategies and food productivity in Nepal: a counterfactual analysis. *Clim. Change* 148, 575–590. <https://doi.org/10.1007/s10584-018-2214-2>.
- Klein, R.J.T., 2009. Identifying countries that are particularly vulnerable to the adverse effects of climate change: an academic or a political challenge? *Carbon Clim. Law Rev.* 3, 284–291.
- Kobziar, L.N., Vuono, D., Moore, R., Christner, B.C., Dean, T., Betancourt, D., Watts, A.C., Aurell, J., Gullett, B., 2022. Wildland fire smoke alters the composition, diversity, and potential atmospheric function of microbial life in the aerobiome. *ISME Commun.* 2, 1–9. <https://doi.org/10.1038/s43705-022-00089-5>.
- Lamsal, P., Kumar, L., Atreya, K., Pant, K.P., 2017. Vulnerability and impacts of climate change on forest and freshwater wetland ecosystems in Nepal: a review. *Ambio* 46, 915–930. <https://doi.org/10.1007/s13280-017-0923-9>.
- Levy, S.J., 2005. The evolution of qualitative research in consumer behavior. *J. Bus. Res. Spec. Sect.: Mark. Commun. Consumer Behav.* 58, 341–347. [https://doi.org/10.1016/S0148-2963\(03\)00107-3](https://doi.org/10.1016/S0148-2963(03)00107-3).
- Lujala, P., Lein, H., Rod, J.K., 2015. Climate change, natural hazards, and risk perception: the role of proximity and personal experience. *Local Environ.* 20, 489–509. <https://doi.org/10.1080/13549839.2014.887666>.
- Magni, G., 2017. Indigenous knowledge and implications for the sustainable development agenda. *Eur. J. Educ.* 52, 437–447. <https://doi.org/10.1111/ejed.12238>.
- Maraseni, T., Poudyal, B.H., Aryal, K., Laudari, H.K., 2022. Impact of COVID-19 in the forestry sector: a case of lowland region of Nepal. *Land Use Policy* 120, 106280. <https://doi.org/10.1016/j.landusepol.2022.106280>.
- Marino, D., Palmieri, M., Marucci, A., Soraci, M., Barone, A., Pili, S., 2023. Linking flood risk mitigation and food security: an analysis of land-use change in the metropolitan area of Rome (Basel) 12, 366. <https://doi.org/10.3390/land12020366>.
- MEA, 2005. Millennium ecosystem assessment. Ecosystems and human well-being: synthesis.
- Mishra, S.R., Bhandari, P.M., Issa, R., Neupane, D., Gurung, S., Khanal, V., 2015. Climate change and adverse health events: community perceptions from the Tanahu district of Nepal. *Environ. Res. Lett.* 10, 034007. <https://doi.org/10.1088/1748-9326/10/3/034007>.
- MoFE, 2019. Climate change scenarios for Nepal for National Adaptation Plan (NAP).
- MoFSC/REDD, 2015. Nepal REDD+ Strategy 2015.
- Morgan, M., Gulliford, M., Anderson, I., 2009. Ethnic minorities and indigenous peoples. In: Detels, R., Beaglehole, R., Lansang, M.A., Gulliford, M. (Eds.), *Oxford Textbook of Public Health*. Oxford University Press, p. 0. <https://doi.org/10.1093/med/9780199218707.003.0087>.
- NAPA, 2010. National adaptation programme of action to climate change (NAPA).
- Nash, N., Capstick, S., Whitmarsh, L., Chaudhary, I., Manandhar, R., 2019. Perceptions of local environmental issues and the relevance of climate change in Nepal's Terai: perspectives from two communities. *Front. Sociol.* 4.
- Neeraja, U.V., Rajendrakumar, S., Saneesh, C.S., Dyda, V., Knight, T.M., 2021. Fire alters diversity, composition, and structure of dry tropical forests in the Eastern Ghats. *Ecol. Evol.* 11, 6593–6603. <https://doi.org/10.1002/ece3.7514>.
- Neupane, P.R., Maraseni, T.N., Köhl, M., 2017. The sugarcane industry in Nepal: opportunities and challenges. *Environ. Dev.* 24, 86–98. <https://doi.org/10.1016/j.envdev.2017.02.001>.
- Nguyen, T.P.L., Seddaiu, G., Virdis, S.G.P., Tidore, C., Pasqui, M., Roggero, P.P., 2016. Perceiving to learn or learning to perceive? Understanding farmers' perceptions and adaptation to climate uncertainties. *Agric. Syst.* 143, 205–216. <https://doi.org/10.1016/j.agry.2016.01.001>.
- NPC, 2024. Sixteenth periodic plan of Nepal (2024/25-2028/29).
- NPC, 2017. Nepal's sustainable development goals status and roadmap: 2016-2030.
- Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. <https://doi.org/10.1126/science.1172133>.
- Ostrom, E., 2007. A diagnostic approach for going beyond panaceas. *Proc. Natl. Acad. Sci.* 104, 15181–15187. <https://doi.org/10.1073/pnas.0702288104>.
- Ostrom, E., Cox, M., 2010. Moving beyond panaceas: a multi-tiered diagnostic approach for social-ecological analysis. *Environ. Conserv.* 37, 451–463. <https://doi.org/10.1017/S0376892910000834>.
- Pandey, H., 2020a. Gorkha earthquake reduces the dependency in forests of Nepal. In: *Abstract of the Conferences. Presented at the International Knowledge Forum. Nepal Alumni Association of the Netherlands*, p. 22. Virtual.
- Pandey, H.P., 2020b. Coordinated Efforts Needed to Manage Disasters. *The Rising Nepal*.
- Pandey, H.P., 2017. Analyze the occurrence of rainfall-induced landslides in a participatory way for mid-hills of Nepal himalayas. *Advancing culture of living with landslides*.
- Pandey, H.P., 2011. Climate change policies and district soil conservation office's activities in Nepal. In: *UNEP-EPLC 5th South-Asian Environment Forum 2011*.
- Pandey, H.P., 2003. Soil Conservation and Watershed Management in Nepal. The Prabhat.
- Pandey, H.P., Aryal, K., Aryal, S., Maraseni, T.N., 2023. Understanding local ecosystem dynamics in three provinces of the lowlands of Nepal. *Sci. Total Environ.* 867, 161501. <https://doi.org/10.1016/j.scitotenv.2023.161501>.
- Pandey, H.P., Gnyawali, K., Dahal, K., Pokhrel, N.P., Maraseni, T.N., 2022. Vegetation loss and recovery analysis from the 2015 Gorkha earthquake (7.8 Mw) triggered landslides. *Land Use Policy* 119, 106185. <https://doi.org/10.1016/j.landusepol.2022.106185>.
- Pandey, H.P., Maraseni, T.N., Apan, A., 2024a. Assessing the theoretical scope of environmental justice in contemporary literature and developing a pragmatic monitoring framework. *Sustainability* 16, 10799. <https://doi.org/10.3390/su162410799>.
- Pandey, H.P., Maraseni, T.N., Apan, A., Bhusal, S., 2024b. Achieving SOC conservation without land-use changes between agriculture and forests. *Sustainability* 16, 7207. <https://doi.org/10.3390/su16167207>.
- Pandey, H.P., Maraseni, T.N., Apan, A., Bhusal, S., 2024c. Decoupling REDD+ understanding of local stakeholders on the onset of materializing carbon credits from forests in Nepal. *For. Ecosyst.* 11, 100239. <https://doi.org/10.1016/j.fecs.2024.100239>.
- Pandey, H.P., Pokhrel, N.P., 2021. Formation trend analysis and gender inclusion in community forests of Nepal. *Trees. For. People* 5, 100106. <https://doi.org/10.1016/j.tftp.2021.100106>.
- Pandit, R., Pörtner, H.-O., Scholes, R.J., Agard, J., Archer, E., Arneeth, A., Bai, X., Barnes, D., Burrows, M., Chan, L., Cheung (William), W.L., Diamond, S., Donatti, C., Duarte, C., Eisenhauer, N., Foden, W., Gasalla, M.A., Handa, C., Hickler, T., Hoegh-Guldberg, O., Ichii, K., Jacob, U., Insarov, G., Kiessling, W., Leadley, P., Leemans, R., Levin, L., Lim, M., Maharaj, S., Managi, S., Marquet, P.A., McElwee, P., Midgley, G., Oberdorff, T., Obura, D., Balgis, E.O., Pascual, U., Pires, A.P.F., Popp, A., Reyes-García, V., Sankaran, M., Settele, J., Shin, Y.J., Sintayehu, D.W., Smith, P., Steiner, N., Strassburg, B., Sukumar, R., Trisos, C., Val, A.L., Wu, J., Aldrian, E., Parmesan, C., Pichs-Madruga, R., Roberts, D., Rogers, A., Diaz, S., Fischer, M., Hashimoto, S., Lavorel, S., Wu, N., Ngo, H., 2021. Scientific Outcome of the IPBES-IPCC Co-Sponsored Workshop On Biodiversity and Climate Change. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.
- Pant, D., Shah, K.K., Sharma, S., Bhatta, M., Tripathi, S., Pandey, H.P., Tiwari, H., Shrestha, J., Bhat, A.K., 2023. Soil and ocean carbon sequestration, carbon capture, utilization, and storage as negative emission strategies for global climate change. *J. Soil Sci. Plant Nutr.* 23, 1421–1437. <https://doi.org/10.1007/s42729-023-01215-5>.
- Paudel, B., Zhang, Y., Yan, J., Rai, R., Li, L., Wu, X., Chapagain, P.S., Khanal, N.R., 2020. Farmers' understanding of climate change in Nepal Himalayas: important determinants and implications for developing adaptation strategies. *Clim. Change* 158, 485–502. <https://doi.org/10.1007/s10584-019-02607-2>.
- Piya, L., Maharjan, K.L., Joshi, N.P., 2012. Perceptions and realities of climate change among the Chepang communities in rural mid-hills of Nepal.
- Porter, L., Rickards, L., Verlie, B., Bosomworth, K., Moloney, S., Lay, B., Latham, B., Anguelovski, I., Pellow, D., 2020. Climate justice in a climate changed world. *Plan. Theory Pract.* 21, 293–321. <https://doi.org/10.1080/14649357.2020.1748959>.
- Poudel, D.D., Duex, T.W., 2017. Vanishing springs in Nepalese mountains: assessment of water sources, farmers' perceptions, and climate change adaptation. *MRED* 37, 35–46. <https://doi.org/10.1659/MRD-JOURNAL-D-16-00039.1>.
- Ranjitkar, S., Sujakhu, N.M., Merz, J., Kindt, R., Xu, J., Martin, M.A., Ali, M., Zomer, R.J., 2016. Suitability analysis and projected climate change impact on banana and coffee production zones in Nepal. *PLoS One* 11, e0163916. <https://doi.org/10.1371/journal.pone.0163916>.
- Roco, L., Engler, A., Bravo-Ureta, B.E., Jara-Rojas, R., 2015. Farmers' perception of climate change in Mediterranean Chile. *Reg. Environ. Change* 15, 867–879. <https://doi.org/10.1007/s10113-014-0669-x>.
- Schlossberg, D., Collins, L.B., 2014. From environmental to climate justice: climate change and the discourse of environmental justice. *WIREs Clim. Change* 5, 359–374. <https://doi.org/10.1002/wcc.275>.
- Shah, K.K., Modi, B., Pandey, H.P., Subedi, A., Aryal, G., Pandey, M., Shrestha, J., 2021. Diversified crop rotation: an approach for sustainable agriculture production. *Adv. Agric.* 2021, e8924087. <https://doi.org/10.1155/2021/8924087>.
- Shahzad, L., Tahir, A., Sharif, F., Khan, W.U.D., Farooq, M.A., Abbas, A., Saqib, Z.A., 2019. Vulnerability, well-being, and livelihood adaptation under changing environmental conditions: a case from mountainous region of Pakistan. *Environ. Sci. Pollut. Res.* 26, 26748–26764. <https://doi.org/10.1007/s11356-019-05880-x>.
- Shi, J., Visschers, V.H.M., Siegrist, M., 2015. Public perception of climate change: the importance of knowledge and cultural worldviews. *Risk Anal.* 35, 2183–2201. <https://doi.org/10.1111/risa.12406>.

- Shrestha, A.B., Aryal, R., 2011. Climate change in Nepal and its impact on Himalayan glaciers. *Reg. Environ. Change* 11, 65–77. <https://doi.org/10.1007/s10113-010-0174-9>.
- Shrestha, U.B., Shrestha, A.M., Aryal, S., Shrestha, S., Gautam, M.S., Ojha, H., 2019. Climate change in Nepal: a comprehensive analysis of instrumental data and people's perceptions. *Clim. Change* 154, 315–334. <https://doi.org/10.1007/s10584-019-02418-5>.
- Shrestha, U.B., Shrestha, B.B., 2019. Climate change amplifies plant invasion hotspots in Nepal. *Divers. Distrib.* 25, 1599–1612. <https://doi.org/10.1111/ddi.12963>.
- Sujakhu, N.M., Ranjitkar, S., Niraula, R.R., Pokharel, B.K., Schmidt-Vogt, D., Xu, J., 2016. Farmers' perceptions of and adaptations to changing climate in the Melamchi Valley of Nepal. *MRED* 36, 15–30. <https://doi.org/10.1659/MRD-JOURNAL-D-15-00032.1>.
- Sylliris, N., Papagiannakis, A., Vartholomaios, A., 2023. Improving the climate resilience of urban road networks: a simulation of microclimate and air quality interventions in a typology of streets in Thessaloniki Historic Centre. *Land* 12, 414. <https://doi.org/10.3390/land12020414>.
- Tesfaye, W., Seifu, L., 2016. Climate change perception and choice of adaptation strategies: empirical evidence from smallholder farmers in east Ethiopia. *Int. J. Clim. Chang. Strateg. Manage.* 8, 253–270. <https://doi.org/10.1108/IJCCSM-01-2014-0017>.
- Thapa, P., 2019. Observed and perceived climate change analysis in the Terai Region, Nepal 7, 303–322. <https://doi.org/10.11216/gsj20191231953>.
- Thorn, J.P.R., 2019. Adaptation “from below” to changes in species distribution, habitat and climate in Agro-ecosystems in the Terai Plains of Nepal. *Ambio* 48, 1482–1497. <https://doi.org/10.1007/s13280-019-01202-0>.
- Tiani, A.M., Bele, M.Y., Sonwa, D.J., 2015. What are we talking about? The state of perceptions and knowledge on REDD+ and adaptation to climate change in Central Africa. *Clim. Dev.* 7, 310–321. <https://doi.org/10.1080/17565529.2014.953901>.
- Tiwari, K., Awasthi, K., Balla, M., Sitaula, B., 2010. Local people's perception on Climate Change, its impact and adaptation practices in Himalaya to Terai regions of Nepal. *Himalayan Research Papers Archive*.
- UIA, 2023. Respecting cultural integrity of indigenous peoples and communities | Global Strategies & Solutions | the Encyclopedia of World Problems and Human Potentials [WWW Document]. URL <http://encyclopedia.uia.org/en/strategy/199275> (accessed 9.19.23).
- Uisso, A.J., Chirwa, P.W., Ackerman, P.A., Mbwapbo, L., 2022. Understanding community awareness, knowledge and perceived importance of land-use plans and village land forest reserves in the context of REDD+ in Tanzania. *Int. For. Rev.* 24, 113–128. <https://doi.org/10.1505/146554822835224784>.
- UN, 2015. The 17 goals: the 2030 agenda for sustainable development [WWW Document]. United Nations. URL <https://sdgs.un.org/goals> (accessed 5.27.21).
- Vaidya, R.A., Sharma, E., 2014. Research Insights on Climate and Water in the Hindu Kush Himalayas. International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal. <https://doi.org/10.53055/ICIMOD.595>.
- Weber, E.U., 2010. What shapes perceptions of climate change? *Wiley Interdiscipl. Rev.: Clim. Change* 1, 332–342.
- White, L.A., 1959. The concept of culture. *Am. Anthropol.* 61, 227–251.
- Yeang, D., 2010. Tenure rights and benefit sharing arrangements for REDD: a case study of two REDD pilot projects in Cambodia. <https://doi.org/10.2139/ssrn.1662042>.
- Yeh, E.T., Nyima, Y., Hopping, K.A., Klein, J.A., 2014. Tibetan pastoralists' vulnerability to climate change: a political ecology analysis of snowstorm coping capacity. *Hum. Ecol.* 42, 61–74. <https://doi.org/10.1007/s10745-013-9625-5>.
- Zheng, Y., Dallimer, M., 2016. What motivates rural households to adapt to climate change? *Clim. Dev.* 8, 110–121. <https://doi.org/10.1080/17565529.2015.1005037>.

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