CHAPTER FOUR

Agronomic, socio-economic, and environmental challenges and opportunities in Nepal's cereal-based farming systems

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Abstract

With economies heavily dependent on agriculture, South Asia is the world's most poverty-dense region. Nepal—a country of considerable geographic variability ranging from population-dense low-elevation Terai region to the sparsely inhabited, poorly accessible Himalayan hills and mountains—has enormous environmental and socio-economic challenges to agricultural development. Runoff from the hills and mountains feed networks of rivers that are crucial for supply of surface and groundwater for the Terai and northern India and Bangladesh, benefitting approximately one-fifth of the world's population. Nepal's farming systems are complex, with insufficient documentation of research evidence on the challenges and opportunities facing them. This review documents the key environmental, socio-economic and agronomic issues affecting cereal-based farming systems in Nepal. Evidences suggest farmers in the hills and mountains primarily practice integrated crop-livestock-tree based agroforestry systems with local varieties of crop and livestock species, and use farm-derived organic amendments and limited external inputs, resulting in low but stable yields. The Terai's cropping systems are predominantly rice-based, with wheat, maize and pulses grown in rotation with low to moderate use of inputs, although high yielding varieties are increasingly common. Major environmental challenges in the high and mid-hills include erosion and soil degradation, while in the Terai, reduced soil fertility and sub-optimal management of water resources are important constraints. Climate variability and extremes are cross-regional challenges. Socioeconomic issues include land use policy, labor out-migration and agricultural feminization. Large gaps between potential and farmers' yields are consistent concerns. While summarizing past and current agronomic research findings, this review suggests new research needs and agricultural development pathways that could address these environmental, socioeconomic and agronomic issues and challenges.

1. Introduction

The Himalayan Mountain range in South Asia stretches from Pakistan in the west to Bhutan in the east, with Nepal in center between China in the north and India in the south. Himalayan ecosystems are rich in biodiversity and dominated subsistence and small-scale farmers with limited market integration. The cultivation of crops and trees are commonly combined with the raising of livestock and remain a primary means of livelihood sustenance for smallholder farmers with diverse social, cultural and ethnic backgrounds (Sandhu and Sandhu, 2015). In these low-external input agricultural systems, farmers practice cropping with family labor and largely with organic inputs recycled within their farm (Chand and Thapa, 1992; Timsina, 2001). Although these systems partially meet the daily caloric and nutritional requirements for farm households, their lack of market integration tends to offer lower economic returns and limited prospects for livelihood improvement (Burris, 2019; IIRR, 1992).

With increasing climatic variability and the prevalence of extreme climatic events such as flooding (Elalem and Pal, 2015), farmers cultivating crops and raising livestock in the Himalayan hills as well as the Terai—the low-lying flatlands that buttress the hills—are considered to be highly susceptible to the localized effects of global environmental change (Elalem and Pal, 2015; Shrestha et al., 2012). Measured over the last two decades, Nepal is among the top 10 vulnerable countries affected most by compound extreme climatic threats including landslides, storms, floods, droughts, heat waves and earthquakes (ADS, 2015; He et al., 2018; Eckstein et al., 2020). Nepal's Agricultural Development Strategy (ADS), which covers the period from 2015 to 2035, suggests that the country holds the 46th position among the 52 countries that fall below the Global Hunger Index that integrates undernourishment and child wasting, stunting, and mortality (ADS, 2015). Nepal's National Adaptation Program of Action (NAPA) to climate change also suggests that the country faces multiple challenges, including glacial melt, flash floods, landslides, and erratic and extreme patterns of rainfall, temperature, and hailstorms (MoSTE, 2010). This adaptation plan also indicates that close to two million people in Nepal are highly vulnerable to climate change, with an estimated 10 million more people who are likely to struggle with climate in the future.

Nepal's population increased by 24% (from 22.5 to 28.0 million) from 1997 to 2017 (FAOSTAT, 2019). Although the country's rural population is several times higher than its urban population, the rate of increase of the latter over the same period was much higher at 5.49% yr^{-1} (Fig. 1), indicative of rapid rural to urban migration (FAOSTAT, 2019; Table 1). The population of Nepal is heavily dependent on cereals as the main source of calorie supply, with rice (*Oryza sativa*), wheat (*Triticum aestivum*), maize (*Zea mays*), and to a lesser extent finger millet (*Eleusine coracana*), barley (*Hordeum vulgare*) and buckwheat (*Fagopyrum esculentum*) being directly consumed. Maize is both directly consumed and also sold as a cash crop, primarily to produce feed for poultry and livestock (Timsina et al., 2016). Finger millet is relatively resilient to drought and hardy conditions and can grow adequately well under conditions of poor soil fertility in hills and montanous areas. It is primarily cultivated in relay with maize, with millet seedlings transplanted by hand into tilled soil (Adhikari, 2012).

During the 1980s, Nepal exported substantial amounts of rice (Pudasainee et al., 2018). However, due to substantially increased consumer demand, relatively low yield growth rates of cereals, and food distributional challenges, 0.54, 0.14 and 0.35 million tons of rice, wheat and maize grains worth

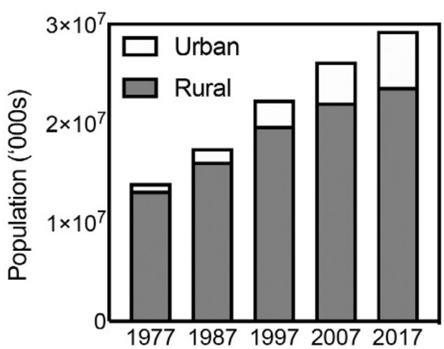


Fig. 1 Rural and urban population increase in Nepal. *Data derived from FAOSTAT, 2019. United Nations Food and Agricultural Organisation. http://www.fao.org/faostat/en/#data.*

Table 1 Comparison of basic parameters across three AEZs of Nepal, 2019.

Parameter	Agroecological zone			
	Terai	Hills	Mountains	Country-wide
Population (million)	14.72	12.33	1.87	28.92
Climate	Humid tropical, sub-tropical	Warm and cold temperate	Arctic/Nival	
Altitude (m)	less than 1500	1500-3000	greater than 3000	59–8848 m
Geographical area (%)	23	42	35	
Cultivated area (%)	38	15	4	
Cropping intensity (%) (lowland)[a]	290	260	160	
Cropping intensity (%) (highland)[a]	240	230	210	
Farm size (ha)	1.26	0.77	0.68	less than 0.70
Mechanization (% farms)	46	6	2	23
Food balance (tons)	+103,662	−88,644	-86,417	−71,399
Fertilizer use (% farm households using fertilizer)	79	61	52	69
Fertilizer use (kg ha^{-1} yr^{-}1)	117	36	20	76
Food supply (g cap^{-1} d^{-1})	n/a	n/a	n/a	524
Food supply (Kcal cap^{-1} d^{-1})	n/a	n/a	n/a	1649
Protein supply (g cap^{-1} d^{-1})	n/a	n/a	n/a	69.2
Environmental issues/constraints	Drought, flooding, high temperature stress	Soil erosion, land degradation, low temperature stress	Soil erosion, land degradation, low temperature stress	

[a]Cropping intensity are for Terai, mid-hills and high-hills; n/a indicates data not available for this level of disaggregation.

Based on FAOSTAT, 2019. United Nations Food and Agricultural Organisation. http://www.fao.org/faostat/en/#data; MoALD, 2019. Statistical Information on Nepalese Agriculture 2017-2018. MoALD, Kathmandu, Nepal; Khatiwada, S.P., Zhang, J., Su, Y., Paudel, B., Deng, W., 2017. Agricultural Land Use Intensity and Determinants in Different Agroecological Regions in Central Nepal Himalaya. In: Li, A. (Ed.), Land Cover Change and Its Eco-environmental Responses in Nepal. Springer. Nature. https://doi.org/10.1007/978-981-10-2890-8_13; Takeshima, H., 2017. Overview of the Evolution Of Agricultural Mechanization in Nepal. Development Strategy and Governance Division. International Food Policy Research Institute, Washington, DC. P. 54. https://www.ifpri.org/publication/overview-evolution-agricultural-mechanization-nepal-focus-tractors-and-combine; Takeshima, H., Bhattarai, M., 2019. Agricultural mechanization in Nepal: Patterns, impacts and enabling strategies for promotion. In: Thapa, G., Kumar, A., Joshi, P.K. (Eds.), Agricultural Transformation in Nepal. Springer: Berlin/Heidelberg, Germany, pp. 261-289.

USD 232, 38.4 and 90.8 million, respectively, were imported in 2017 (FAOSTAT, 2019). Considering optimistic production scenarios and per capita demand of 119.5, 22.0 and 30.6 $kg yr^{-1}$ of rice, wheat and maize, Prasad et al. (2012) nonetheless projected a total human demand deficit of 41.1% for rice, and surplus of 74.9% and 64%, respectively, for wheat and maize, in 2030. The surplus for wheat and maize were mainly due to consideration of per capita demand for human needs only without considering demands for animal feed and other uses. Estimates are that Nepal has a net positive annual cereal food balance (103,662 tons) in the Terai—which is Nepal's most intensive cereal production at the foot of the Himalayan hills and the northern-most edge of the Indo-Gangetic Plains—and a net negative balance (−175,061 tons) in the hills and mountains. This resulted in a country-wide net negative cereal balance (−71,400 tons) in 2017 (FAOSTAT, 2019). In addition to the importance of domestic food supply, agricultural activities generate income and employment for more than 66% of Nepali households, respectively, while also contributing 28% to the country's gross domestic product (Adhikari, 2015; World Bank, 2019). The Government of Nepal has also developed national agricultural sector action plans that target achieving a food grain trade surplus of at least 5% by 2035, while increasing and maintaining GDP from agricultural activities at 20%, reducing poverty to 10%, and achieving zero hunger through self-reliance on food production (ADS, 2015; MoAD, 2016).

In addition to these concerns, Nepal's increasing population has largely outpaced the stable income growth opportunities for rural populations—and particularly young men. This has resulted in increased migration to urban areas in the Terai, and in many cases is a driving force for out-migration to India, the Middle East, and South East Asia, where young men work as laborers and send remittances back to their families (Jaquet et al., 2019; Lipton, 1980; Maharjan et al., 2013a). In 2019, Nepal was the fourth highest recipient of remittances from migrant laborers in South Asia after India, Pakistan and Bangladesh, receiving $8.1 billion. This ranks Nepal the highest among South Asian countries in terms of the relative importance of remittances for economic development, with particular ramifications for rural areas (World Bank, 2019). Currently, more than 0.5 million youth below 30 years of age migrate annually. This trend is also increasing (GoN, 2014; MoF, 2019), resulting in increased labor wage rates for crop production (Fig. 2). As a consequence of out-migration, Nepal has been experiencing a decline in rural labor availability and increasing rural labor costs, a situation which has negative consequences for subsistence and

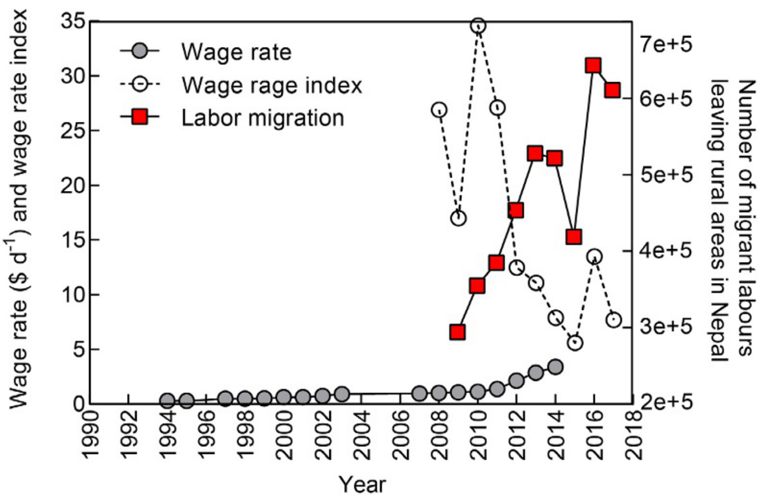


Fig. 2 Trends in yearly youth migration from Nepal for employment, and wage rates in crop production in Nepal. *Data from GoN, 2014. Labour Migration for Employment. A Status Report for Nepal: 2013/2014. Ministry of Labour and Employment Kathmandu, Nepal. P.74. https://asiafoundation.org/resources/pdfs/MigrationReportbyGovernmentofNepal.pdf; MoF, 2019. Economic Survey 2018/19. Government of Nepal, Ministry of Finance (MoF), Singh Durbar, Kathmandu. Page 256, URL: https://mof.gov.np/uploads/document/file/compiled%20economic%20Survey%20english%207-25_20191111101758.pdf. Last Accessed: 29 September 2020.*

market integrated farmers alike, at times resulting in delays in key agricultural operations and an increase in women's responsibilities as farm management decision makers (Bhandari et al., 2015). Labor migration from the Himalayas of South Asia and particularly Nepal has also been described as a major factor influencing seasonal land fallowing and land degradation (Chaudhary et al., 2018; Khanal et al., 2015; Khanal, 2018; Khanal and Watanabe, 2006; Maharjan et al., 2013b; Paudel et al., 2019a; Wang et al., 2016). Conversely, with the advent of the COVID-19 crisis in early 2020, more than 0.4 million migrant laborers have been or could be repatriated from India to Nepal (ILO, 2020). The potential impact of this return migration—which although large, is still a relatively small proportion of the combined numbers of annual migrants and those in the Middle East and South East Asia—on Nepal's agricultural systems, remains unclear. What is however clear is that the combination of these socioeconomic challenges and biophysical constraints have influenced changes in farmers' land and resource use and management practices (Chapagain and Raizada, 2017; Jaquet et al., 2019; Paudel and Thapa, 2001), resulting in increased risk and stagnant income generation from non-diversified, cereal-based cropping systems (Dawadi, 2016).

Changes in land use and land management practices in Nepal have implications for other South Asian countries with similar topographical variation and socio-economic characteristics. In Nepal, the bulk of food production comes from the Terai, the Inner Terai (broad valleys located at higher elevation than the Terai, but lower and less rugged than the hills, and mid-hill regions). The chief source of surface and groundwater in these areas originates in the Himalayas, although flow is variable, particularly for surface water that becomes increasingly constrained in the dry winter season (Bartlett et al., 2010). Soil fertility and quality in Terai, on the other hand, is affected by underlying pedology, the flow of alluvium and colluvium from the mountains and hills, as well as farmers' management practices. In addition to environmental phenomena, the flow of sediments from the mountains and hills is affected by anthropomorphic climate change, land clearing and poor land use management practices (Tiwari, 2000). As such, this review focuses on Nepal's Terai, Inner Terai and mid-hill regions where cereal-based cropping systems are most common, although where relevant, links are made to the high-hill and mountain regions.

We used a pragmatic methodological approach to conduct this literature review. We searched published peer-reviewed papers from Science Direct, Scopus and Web of Science. We also analyzed long-term climatic trends, and available land management and crop production statistics published by research organizations and/or the Government of Nepal. In addition, resources including Google Scholar, Research Gate and Academia were also reviewed to identify relevant peer-reviewed papers, reports, and working papers. We also present relevant crop model simulation results from published literature and from ongoing studies. These sources were supplemented by key informant interviews of researchers and policy makers in national agricultural research centers, and in the Agricultural and Forestry and Tribhuvan Universities, in addition to field visits to representative locations. These sources were used to verify and moderate the information collected from reports and crop production statistics. Using this methodology, we identified potential suites of improved management practices for the development of productive and more environmentally sensitive cereal-based crop production systems. We sought (a) to provide a succinct summary of information to integrate and document the environmental and socio-economic issues affecting cereal-based production systems in Nepal. We focus primarily on the three key cereals produced and consumed or sold in Nepal, including rice, wheat, and maize, although we also consider issues that pertain to finger millet, which is the fourth widely grown cereal in Nepal (Khadka et al., 2016b). In addition, we aimed (b) to identify research gaps in these areas, and (c) to provide recommendations for the potential improvement of these farming systems. Finally, we (d) provide policy suggestions to assist in guiding more sustainable land and resource use management in Nepal, while addressing cereal-based cropping systems in the hills and Terai in particular.

2. Agroecological regions and farming systems

2.1 Agroecological regions

Nepal, with a total land area of 147,516 km^2, lies between 26°22′-30°27′ N and 80°04′-88°12′ E respectively, and can be broadly divided into three primary east-west running agroecological regions (agroecological zones). These include the Terai and Inner Terai in the Indo-Gangetic Plain that run from the south-west to south-east of Nepal at elevations typically below 800 m. The mid-hills in north of Terai and Inner Terai are typically between 800 and 1800 m, with the high-hills and mountains sequentially buttressing the mid-hills at above 1800 m.

The Terai and Inner Terai comprise 23% and 38% of Nepal's land and cultivated areas, respectively. They consist mostly of flat and some undulating land, with slope less than 15° in general. The Inner Terai are represented by higher elevation valleys such as the Dang and Surkhet Valleys, which are separated from the Terai by higher elevation hills, but which remain lower elevation than the hills themselves (Li and Deng, 2017). The mid-hills conversely occupy 42% and 15% of Nepal's geographic areas, respectively. Cultivated land consists of low to steep sloping lands ranging from 15 to 30°. River or stream-cut valleys are prominent features of the mid-hills. The high-hills and mountains cover very steep (>30° slope), severe cold and snow covered areas. These comprise 35% of Nepal's geographic area, though only 4% of land is cultivated (Paudyal et al., 2001) (Fig. 3; Jarvis et al., 2008).

Dijkshoorn and Huting (2009), identified five physiographic regions in Nepal, including the Terai (60–330 m, 14% of Nepal's land area), Siwaliks (< 1000 m, 13% area), the middle mountains (1001–2500 m, 30% area), the high mountains (2501–3500 m, 20% area), and the high Himalaya (> 3501 m, 23% area). In addition, they specified 17 distinct soil and terrain units, 53 sub-terrains, and 118 soil sub-components, largely based on the land system classification developed by Carson et al. (1986). Figs. 4–6

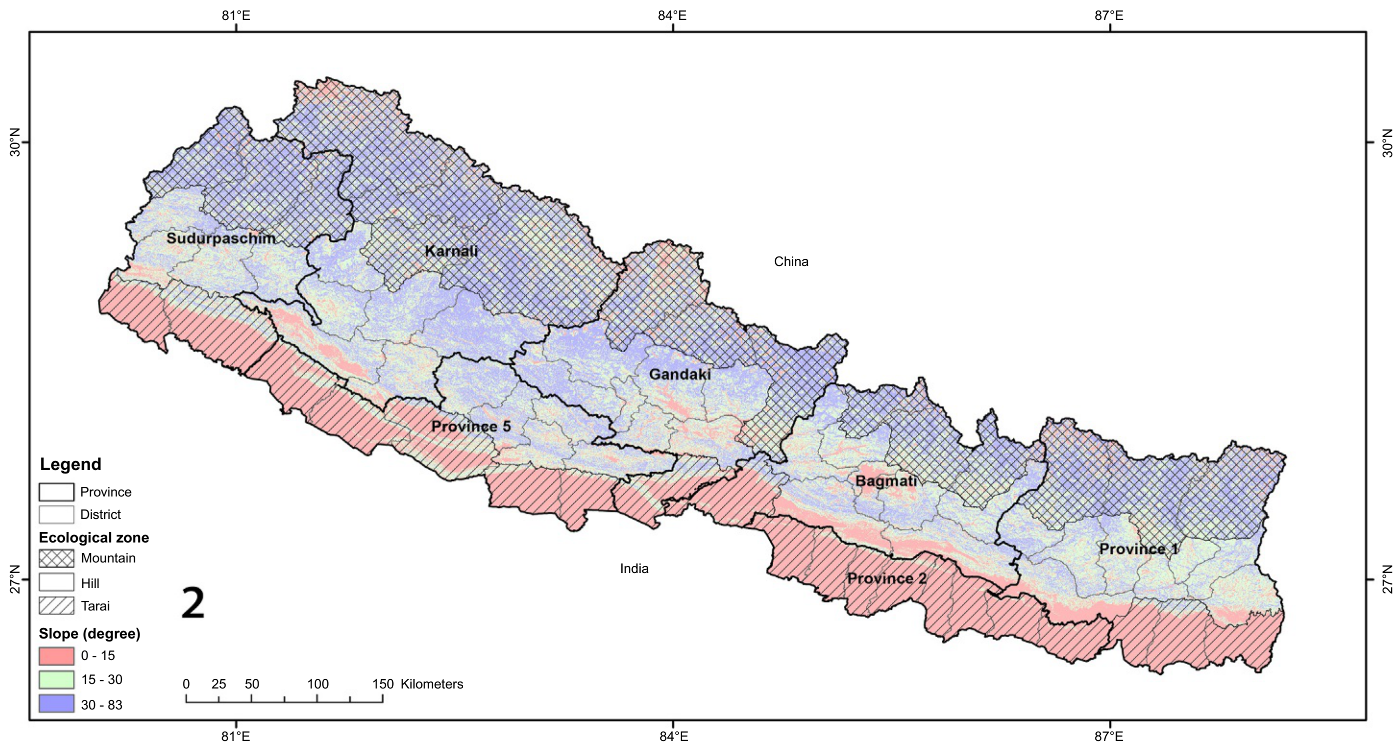
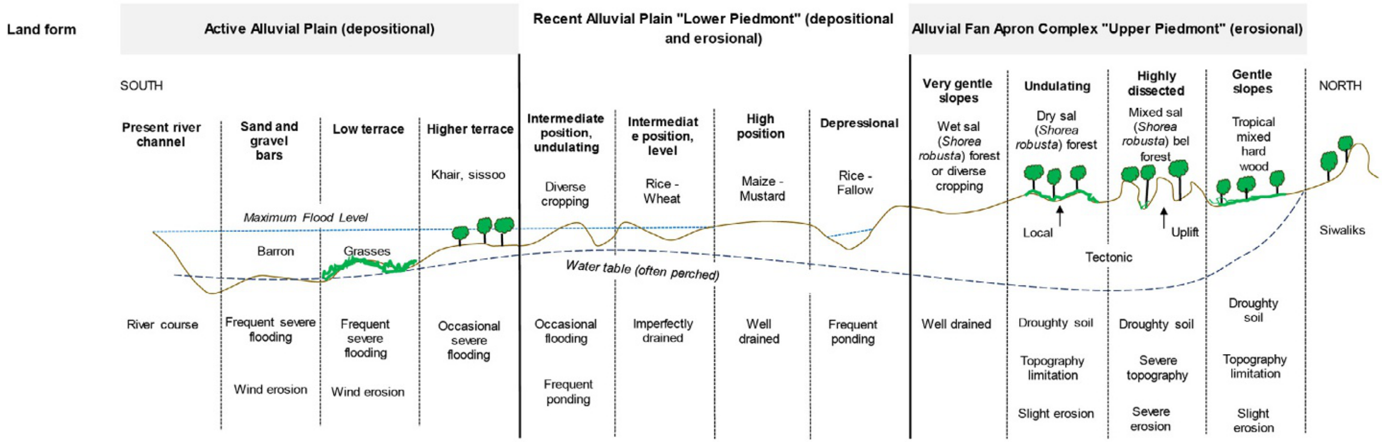
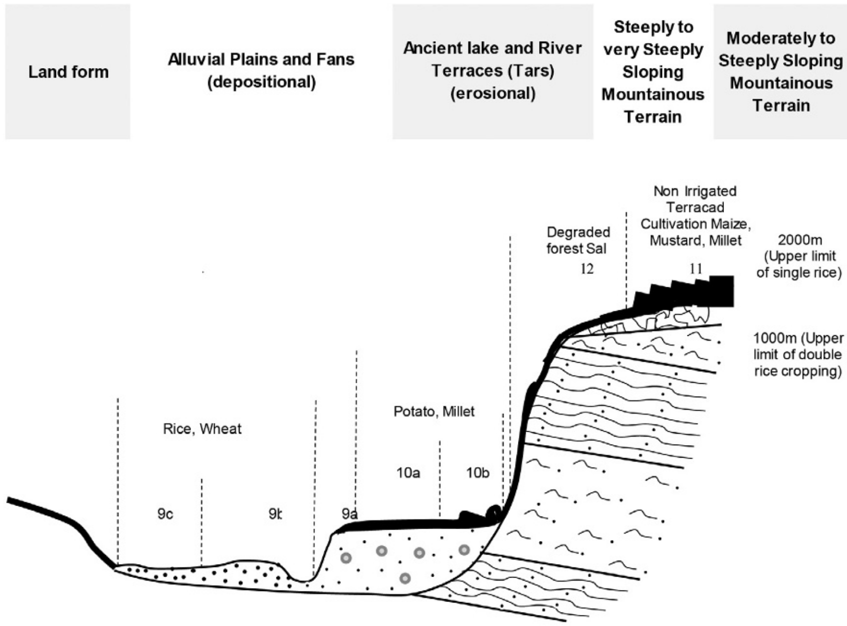


Fig. 3 Map of Nepal depicting three primary agroecological zones, seven provinces and slope. *Data from Jarvis, A., Reuter, H.I., Nelson, A., Guevara, E., 2008. Hole-filled SRTM for the globe Version 4. Available from the CGIAR-CSI SRTM 90m Database. http://srtm.csi.cgiar.org, for slope.*



Land System	1				2				3			
Land Unit	Present river channel	Sand and gravel bars	Low terrace	Higher terrace	Intermediate position, undulating	Intermediate position; level	High position	Depressional	Very gentle slopes	Undulating	Highly dissected	Gentle slopes
Dominant soils	—	Ustorthents Psamments	Ustifluvents Fluvaquents	Ustochrepts Haplaquepts	Haplaquepts Ustochrepts	Haplaquepts (Aeric)	Haplaquepts Ustochrepts	Haplaquepts	Haplustolls Dystochrepts Ustochrepts	Haplustalls	Ustochrepts	Haplustalls
Dominant Slopes	—	< 1°	< 1°	< 1°	< 1°	< 1/2°	< 1°	< 1/2°	< 1°	1 - 3°	0 - 20°	1 - 5°
Dominant Texture	—	Sandy / Cobbly	Sandy	Loamy	Variable	Loamy	Loamy	Fine loamy	Loamy	Loamy	Loamy	Loamy / Bouldery
Seasonal Range of Depth to Water Table	—	0- 2 m	0- 2 m	0- 4 m	Dependent on position	0- 6 m	0 - 10 m	0- 2 m	0 - 10 m	2 - 10 m	> 2 m	2 - 10 m
Drainage	—	Subject to severe river flooding	Variable; subject to severe river flooding	Variable; subject to occasional river flooding	Variable; low areas subject to flooding	Imperfect	Moderately good	Poor	Moderately good	Good	Rapid	Rapid

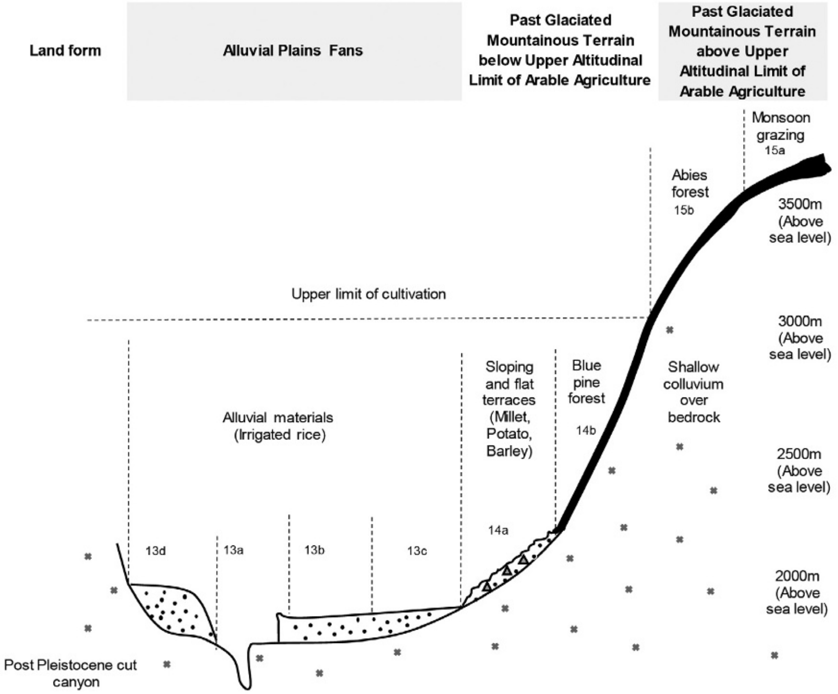
Fig. 4 Schematic cross section of land and physiographic systems in Terai derived based on watershed conditions. *Adapted from Dijkshoorn, K., Huting, J., 2009. Soil and Terrain Database for Nepal. Report 2009/01. ISRIC-World Soil Information, Wageningen. 29p. http://www.isric.org*.



Land System	9			10		12	11
Land Unit	Alluvial fans (9c)	Alluvial plains (9b)	River channel (9a)	Non-dissected (10a)	Dissected (10b)	—	—
Dominant soils	Ustochrepts Haplustalfs	Ustifluvents Fluvaquents Ustochrepts	Psamments Ustarthents	Typic and Rhodic Haplustalfs Ustochrepts	Typic and Rhodic Haplustalfs Ustochrepts	Lithic Subgroups of II and Ustorthents	Typic and Rhodic, Udic, Anthropic Subgroups of Ustochrepts Dystrochrepts Haplumbrepts
Dominant Slopes	1 - 5°	< 1°	< 1°	0 - 5°	0 - 5°	< 30°	< 30°
Dominant Texture	Loamy / Bouldery	Loamy / Bouldery	Fragmental Sandy	Loamy	Loamy	Loamy Skeletal	Loamy Skeletal
Seasonal Range of Depth to Water Table	1- 15 m	0- 2 m	0- 2 m	> 2 m	> 2 m	< 50 cm to bedrock	> 50 cm to bedrock
Drainage	Good	Good	Variable	Good	Good	Good	Moderately good

Legend
Recent alluvium | Old alluvium (Tar) | Phyllite | Quartzite | Saprolite | Colluvium

Fig. 5 Schematic cross section of land and physiographic systems in the mid-hills derived based on watershed conditions. *Adapted from Dijkshoorn, K., Huting, J., 2009. Soil and Terrain Database for Nepal. Report 2009/01. ISRIC-World Soil Information, Wageningen. 29p. http://www.isric.org*.



Land System	13				14		15	
Land Unit	Ancient alluvial terraces (13d)	Active alluvial plain (13a)	Recent alluvial plain (13b)	Fans (13c)	Steep to very steep slopes (14b)	Moderate to steep slopes (14a)	Very steep slopes (15b)	Moderate to steep slopes (15a)
Dominant soils	Eutrochrepts Dystrochrepts	Ustifluvents	Eutrochrepts Dystrochrepts	Eutrochrepts Dystrochrepts	Lithic Subgroups of 14a and Ustorthents	Anthropic and Typic Eutrochrepts Dystrochrepts Haplumbrepts	Lithic Subgroups of 15a and Cryarthents	Typic and Lithic Haplumbrepts Cryumbrepts
Dominant Slopes	< 5°	< 1°	< 2 °	1 - 10°	> 30°	< 30°	> 40°	< 40°
Dominant Texture	Loamy / Bouldery	Loamy	Loamy / Bouldery	Loamy / Bouldery	Loamy Skeletal	Loamy Skeletal	Loamy Skeletal	Loamy Skeletal
Seasonal Range of Depth to Water Table	> 2 m	0- 2 m	0- 2 m	> 2 m	< 50 cm to bedrock	> 50 cm to bedrock	< 20 cm to bedrock	> 20 cm to bedrock
Drainage	Moderately good	Variable	Moderately good	Good	Good	Moderately good	Moderately good	Moderately good

Legend
Gneisses · Landslide colluvium · Glacial till mixed with colluvium

Fig. 6 Schematic cross section of land and physiographic systems in high-mountains derived based on watershed conditions. *Adapted from Dijkshoorn, K., Huting, J., 2009. Soil and Terrain Database for Nepal. Report 2009/01. ISRIC-World Soil Information, Wageningen. 29p. http://www.isric.org.*

provide detailed information for the Terai, Middle Mountain and High Mountain physiographic regions. The terms Siwaliks was applied by Dijkshoorn and Huting (2009) to refer to the Inner Terai and lower hills. They specified the term mountains for what are otherwise commonly termed the hills, and the term Himalaya for mountainous areas.

Hagen (1998), on the other hand, divided Nepal into seven physiographic regions including the Terai, Siwalik, Mahabharat, Mid-hills, Himalayas, Inner Himalayas and Tibetan marginal Mountain range. In this review, which focuses on agricultural systems, we make use of the agroecological classifications of the Terai and Inner Terai, hills (including mid- and high-hills), and mountains. Within these regions, a variety of cereals are grown, although rice, wheat and maize are the primary staples or cash crops produced. Finger millet, barley, buckwheat, and finger millet are also common in hills and mountains, though to a far lesser extent in the Terai. Among these regions and crops, the mountainous areas, followed by the hills, both experience food balance shortages, while the more fertile and productive Terai has food surpluses in most years (Fig. 7; FAOSTAT, 2019; MoALD, 2019).

2.2 Cropping seasons and land area under cereals

While variability in climate, physiography and soils can vary considerably among Nepal's agroecological zones, three farming seasons are generally recognized. These include (a) the summer or monsoon season during which rice is the primary crop in the Terai and mid-hills and maize and millet in high-hills, (b) the dry winter season, during which wheat is widely grown

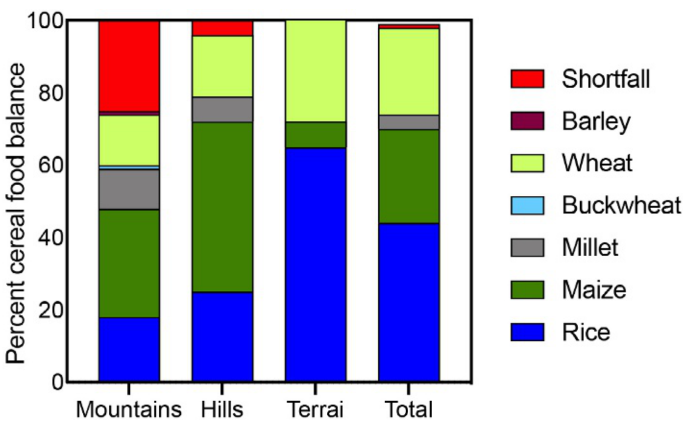


Fig. 7 Typical percent food balance across major cereals in Nepal's agroecological regions.

followed by potato, oilseeds and pulses across all regions but also maize in the Terai, and (c) the spring season, during which maize is commonly grown in the lower-hills and basin areas. Maize, lentil (*Lens culinaris*) and mungbean (*Vigna radiata*) are also grown in the Terai in the spring (Fig. 8). Rice can also be grown in the spring season, and the expansion of spring rice area is a recent agricultural development goal that has been emphasized by the Government of Nepal (Bhandari et al., 2017). The precise start and end date for each of these seasons varies somewhat as a function of location and climate and therefore overlaps slightly, although spring typically commences with the onset of pre-monsoon season rainfall, typically in March to June, while the summer monsoon begins with the formal onset of sustained rains from June–July through October–November. The dry season typically occupies the period from October–November through April.

These four most common cereals produced in Nepal are grown on approximately 3.45 million ha, which is 23% of the country's total land area (MoALD, 2019). Rice is by far the most commonly cultivated cereal (1.55 million ha), followed by maize (0.95 million ha) and wheat (0.74 million ha). Millet is comparatively minor, grown on 0.26 million ha, primarily in the hills and mountains (Fig. 9).

2.3 Major cropping systems in the hills and terai

The potential productivity of a crop at any site is determined by climate and a crop's genetic characteristics, and when water, nutrients and pests are not limiting to growth (Penning de Vries et al., 1989). The adoption of a cropping system however is not determined only by farmers' interest in achieving a given level of production; rather, socio-economic characteristics such as labor availability, organizat risk, input and output prices, social and dietary preferences, government policies, and extension and marketing support services influence crop and management choices (Mazvimavi and Twomlow, 2009; Shiferaw et al., 2009). In the hills and mountains of Nepal, and largely in the Himalayan region of South Asia, indigenous customs, social practices, ethnicity and gender also influence farmers' choice of crops and cropping systems (Schroeder, 1985). For resource-poor farm households located in hills and Terai, government subsidies and credits for purchasing farm inputs, as well as opportunities to avail agricultural services (such as mechanized land preparation or harvesting), can be important factors affecting the use of agronomic technologies and practices. Remote households however may not always be aware of or able to access these support mechanisms.

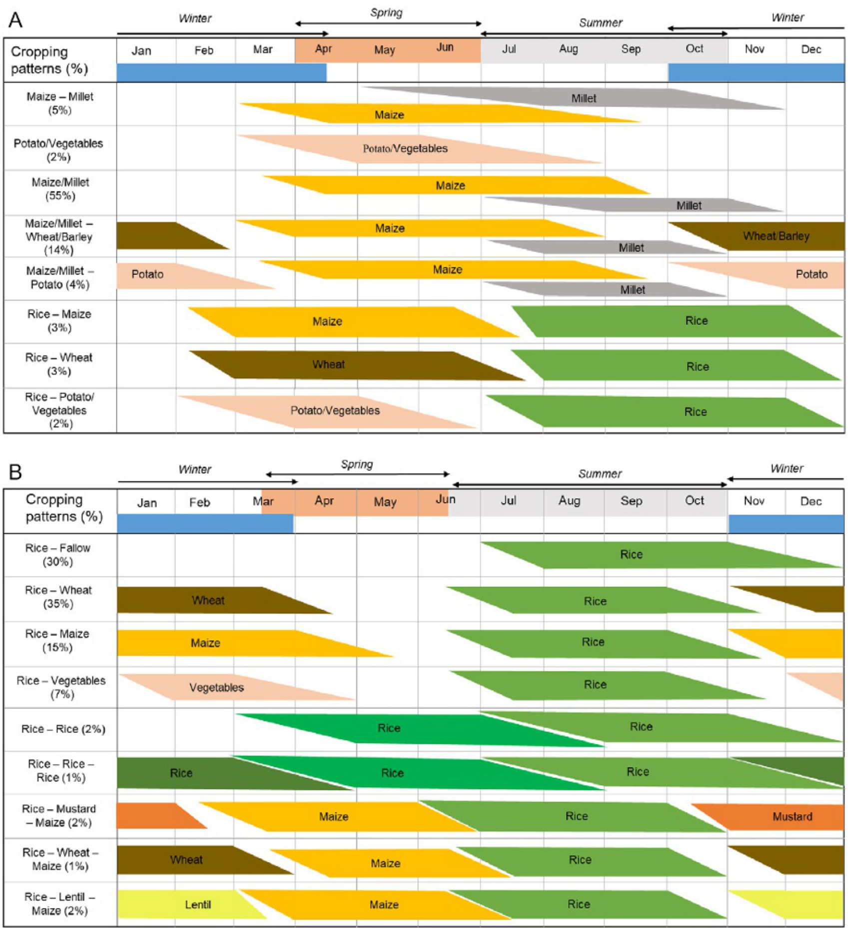


Fig. 8 Major cropping sequences on an annual basis for the (A) mid- and high-hills and (B) Terai and Inner Terai: (A) Potato/vegetables-fallow rotations are practised only in the high-hills, while rice-wheat system also includes rice–wheat+oilseed rotations. In all systems, soybean, pigeon pea, black gram and fodder species may be grown on rice bunds in valleys and river terraces. In river basins, valleys and lower slopes in Nepal's mid-hills, approximately 5% of cropped area are occupied by other double (e.g., rice-chickpea) and triple cropping systems (e.g., rice-potato-spring maize, rice-vegetables-spring maize, rice-wheat-spring maize, rice–wheat+oilseed–spring maize, etc.). In river basins, valleys and also the lower slopes of the mid- and high-hills, approximately 7% cropped area is occupied by other crops, which may include vegetables, fruits, fodder species, or may be maintained in pastures with or without cereals in systems. (B) Rice followed by dry season fallowing tends to be is practised primarily in non-irrigated areas. Rice-vegetable or alternative crop rotations also include potatoes, chickpeas or other crops. Approximately 5% of cropped area is occupied by triple cropping systems (e.g., rice-wheat-mungbean and rice-rice-wheat rotations). In all systems, soybean,

Cropping systems in the Terai and Inner Terai predominantly follow a summer rice–winter wheat rotational system, although cultivation of maize after rice and rice-pulse rotations are also increasing. In the hills, maize-based systems are more common, and many fields may be cropped only once per year. In the high-hills and mountains, millet, barley, buckwheat and other minor crops are common (Timsina, 2001; Timsina and Connor, 2001; Timsina et al., 2016). Haffner (1984) reviewed farming systems in Nepal

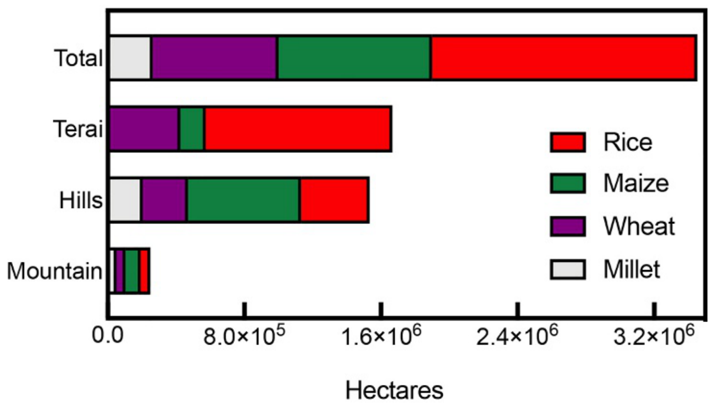


Fig. 9 Land area under Nepal's four major cereals as a function of agroecological region. *Data from FAOSTAT, 2019. United Nations Food and Agricultural Organisation. http://www.fao.org/faostat/en/#data; MoALD, 2019. Statistical Information on Nepalese Agriculture 2017–2018. MoALD, Kathmandu, Nepal.*

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pigeon pea, black gram and fodder and tree species may be cultivated on rice bunds, especially in the Inner Terai. The percentages of different cropping patterns in each region are derived from assessments of relevant published literature cited in the paper and discussions with key informants. *Modified from Paudel, G.S., Thapa, G.B., 2001. Changing farmers' land management practices in the hills of Nepal. Environ. Manage. 28, 789-803. https://doi.org/10.1007/s002670010262; Paudel, S., Zhang, J., Su, Y., Paudel, B., Deng, W., 2017. Agricultural land use intensity and determinants in different agroecological regions in Central Nepal Himalaya. In: Li, A., Deng, W., Zhao, W. (Eds.). Land Cover Change and Its Eco-environmental Responses in Nepal. https://doi.org/10.1007/978-981-10-2890-8; Raut, N., Sitaula, B.K., Aune, J.B., Bajracharya, R.M., 2011. Evolution and future direction of intensified agriculture in the central mid-hills of Nepal. Int. J. Agric. Sustain. 9, 537-550. https://doi.org/10.1080/14735903.2011.609648; Timsina, J., 2001. Working with farmer groups—experiences, benefits, and problems. J. for Farming Systems Research and Extension (Special Issue). International Farming Systems Association. pp. 29-56; Timsina, K.P., Ghimire, Y.N., Lamichane, J., 2016. Maize production in mid hills of Nepal: From food to feed security. J. Maize Res. Dev. 2(1), 20-29. https://doi.org/10.3126/jmrd.v2i1.16212; in addition to expert consultation.*

and reported that arable subsistence systems are practiced as high as 4000 m, with the grazing of yaks at over 5000 m. Double cropping is however limited at high-altitude areas above 3000 m due to the prevalence of frost. Cropping systems in the hills and Terai are continuously evolving and changing in response to households' food and dietary demands, in addition to new market opportunities, and in consideration of the availability of labor and other resources.

The cropping season on each agroecological zone varies by location and climate. In the winter season, crop growing periods are affected largely by temperature regimes (Timsina et al., 2010, 2011). The high-hills are characterized by the longest dry winter and shortest spring and summer season. Conversely, the Terai tends to have a comparatively shorter winter season and longer summer than the mid- or high-hills (Paudyal et al., 2001). Research has also indicated a progressive shortening of winters over time (Bartlett et al., 2010). Across agroecological zones, summer rice is mainly rainfed, and may be augmented with supplementary irrigation from surface and groundwater to support crop growth and to overcome within-season drought (Urfels et al., 2020, 2021; CSISA, 2019). In the winter and spring seasons, however, crops are either fully or partially irrigated in the Terai and Inner Terai and in river basins in the mid- or high hills, using either surface or ground water.

A large number of diverse cropping systems are practiced in each of these agroecological zones (Acharya, 2017; Paudyal et al., 2001; Timsina, 2001). Cropping intensity, defined as the number of crops grown on the same field within the calendar year, ranges from 100% to more than 300%, and is higher in Terai and mid-hills compared to high-hills (Paudel, 2016a,b; Paudel et al., 2017; Timsina, 2001). This is primarily due to differences in altitude, temperature, number of frost-free days, and availability of irrigation, in addition to socioeconomic factors such as access to markets and availability of inputs that affect farmers' interest in multiple cropping (Paudyal et al., 2001; Timsina, 2001; Raut et al., 2011). Rice, maize, wheat and potato (*Solanum tuberosum* L.) are grown in all agroecological zones, but millets, barley and buckwheat are also found in the mid- and high-hills (Fig. 8). Nepal's high and mid-hills are rich in agrobiodiversity, and famers commonly cultivate species of spices, herbs and medicinal plants in home gardens and in household agroforestry systems (Gaire and Subedi, 2011). In all agroecological zones, and especially in the mid- and high hills, livestock, poultry and agroforestry constitute important components of integrated farming systems, with livestock and poultry being important sources of protein and income for households (Khadka and Ghimire, 2005; Timsina, 2001).

2.4 Land use changes

Land use patterns in Nepal and many parts of eastern India are changing rapidly. Considering the countries of South Asia that comprise portions of the Himalayan mountain range, Nepal ranks last in terms of per-capita land availability, with a slow decline from 0.17 ha person^{-1} in 1961 to 0.07 ha person^{-1} in 2017 (World Bank, 2020). Pakistan, Bhutan, and India conversely lost per capita arable land at a rate of 77%, 69% and 65%, respectively, in the same period, though each retained more land per person than Nepal (Fig. 10). Rural out-migration and land use changes, including progressive urbanization, have resulted in increased land abandonment and fallowing, the latter particularly during the winter followed by spring (dry) seasons. This pattern is most evident in the hills. These trends are in opposition to government policies favoring agricultural intensification (ADS, 2015).

2.4.1 Agricultural land abandonment

In many situations and across all ecological regions of Nepal, land fallowing has led to eventual land abandonment—particularly in the hills and mid-hills. These changes can result in the cessation of agricultural activities, causing cultural and social, in addition to agricultural changes (Khanal, 2018). Land fallowing and farmland abandonment is often tied in the

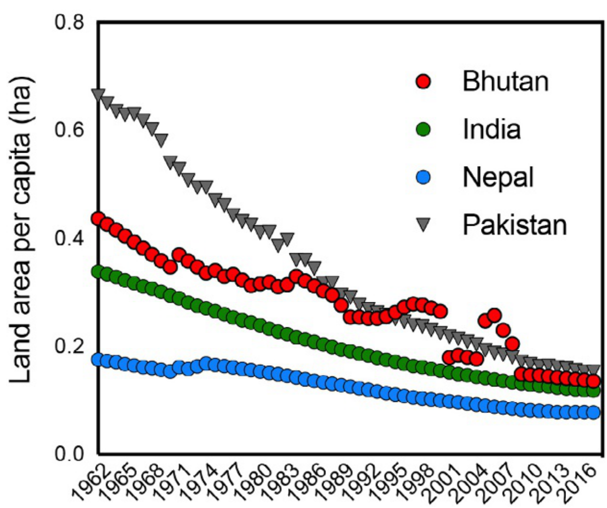

Fig. 10 Changes in per-capita land availability in four South Asian countries. *Data from World Bank, 2020. Arable Land (Hectares)—Agricultural and Rural Development Indicator. https://data.worldbank.org/indicator/AG.LND.ARBL.HA.*

literature to labor shortages, which have become a major challenge in efforts to maintain soil fertility, and to improve the productivity of resource-intensive crops, for example horticultural operations that require higher rates of labor investment than cereals. These issues are in addition to challenges to investment in inputs (Shrestha and Pokhrel, 2016). To tackle land fallowing and farmland abandonment, appropriate farm mechanization, contract and cooperative farming have been proposed as potential partial solutions to improve land use efficiency (Ba et al., 2019). These approaches have also been suggested as a mechanism to increase farm income and provide employment—particularly through job creation for machinery owners that offer land preparation, planting, irrigation, harvesting and post harvesting services to farmers on a fee-for-service basis (CSISA, 2019; Paudel et al., 2019b)—while improving general welfare in rural areas (Meemken and Bellemare, 2019).

Farmland abandonment is widespread across the Himalayas, and is expected to increase further in future (Naz and Romshoo, 2012; Shrestha, 2014; Yamaguchi et al., 2016). Land fallowing and land abandonment can have important implications for short- to medium-term erosion and soil and nutrient losses, enhancing degradation processes (Bajracharya and Sherchand, 2009; Chaudhary et al., 2018; Khanal and Watanabe, 2006; Shrestha and Zinck, 2001). Similarly, conducting a study in the Gandaki River Basin in the western mid-hills, Khanal and Watanabe (2006) showed that approximately 49% of all valley bottoms and 37% of all uplands had been fully abandoned from agricultural and intensive land use. As a result, approximately 10% of all valley bottoms had been damaged by landslides and floods, with about 41% of all abandoned land from valley bottoms to ridge crests experiencing different forms of geomorphic change and damage.

Unless actively managed through restoration efforts, abandonment can result in heightened land degradation (Chaudhary et al., 2020; KC and Race, 2019), in addition to changes in sociocultural relationships among farmers and villagers (Chaudhary et al., 2020). Chaudhary et al. (2018) reported that accessibility to roads, the distance from households to fragmented farm fields, household sizes and the age of the household head, farmland ownership and the landowner's place of residency, in addition to the proportion of farm household income from salaries, business, and remittances, were major variables explaining the extent of farmland abandonment in the high mountainous region of Nepal. Lower accessibility to roads, greater distances from households to fields, smaller household sizes, more elderly household heads, and use of remittances for children's education, health and other activities instead of farming were also factors leading to degradation. Their analysis also suggested that farmers' social and indigenous governance systems, as well as land management practices and village infrastructure (schools, banks, health posts, temples, etc.) are being altered and potentially lost with progressive farmland abandonment and rural outmigration. They also observed a decline in individual and social participation in intensive land management practices, leading to increased invasion from exotic vegetation and soil erosion that led to notable modifications in the physical and ecological characteristics of abandoned farmlands.

2.4.2 Land cover

Land fallowing and youth migration have resulted in rapid rates of urbanization in both the hills and Terai of Nepal, as well as outflux to other countries. Rimal et al. (2018) showed that urbanization increased from 221 km^2 in 1989 to 930 km^2 in 2016, of which 658 km^2 (or 93%) occurred on previously cultivated land. The remaining 7% came of conversion previously forested land and unused sandy areas adjacent to rivers (Rimal et al., 2018; Table 2). Similarly, a case study from the Upper Roshi Watershed in Kavrepalanchowk district in the mid-hills showed that between 1976 and 2000, there were land area increases in broadleaf and conifer forests and lowland cropped areas, but also decreases in shrublands and grasslands and upland cropped areas (Gautam et al., 2003; Table 3). Furthermore, increased fragmentation of lowland agricultural areas was observed, due to the expansion of settlements and progressive infrastructural development. Uddin et al. (2015) reported country-wide land cover and use data using Landsat Thematic Mapper satellite images at a 30 m spatial resolution for 2009, 2010 and 2011. These data showed that forests remain the dominant form of land cover with 57,538 km^2 in Nepal (39.1% of country's geographical area). This is followed by agricultural area (excluding grazing land), which amounts to approximately 43,910 km^2 (29.8% area). The remaining areas are under grasslands, shrublands, lakes and glaciers, and built-up land. There are five physiographic regions: the high mountains, middle mountains, hills, Siwalik, and Terai. Hilly areas had larger areas under forest (22,621 km^2; 30.5%) as well as cultivated land (19,783 km^2; 45.1%), while the Terai region had more cultivated land (14,104 km^2; 32%) and comparatively less forested area (4280 km^2; 5.8%). The middle mountains had also large areas under forest or natural land cover (32.6%). The high mountainous region was predominantly under natural water bodies and snow and glaciers (93.2%) (Uddin et al., 2015; Table 4).

Table 2 Land cover/use changes during six periods between 1989 and 2016 in the Terai region of Nepal.

	1989		1996		2001		2006		2011		2016	
Land use	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**
Urban	221	0.66	272	0.81	3823	1.1	486	1.45	793	2.37	930	2.78
Cropland	16,670	49.8	16,733	50	16,598	49.6	16,431	49.1	16,130	48.2	16,001	47.8
Natural vegetation	14,100	42.1	14,041	41.9	14,043	41.9	14,081	42.1	14,025	41.9	14,091	42.1
Barren land	91	0.27	76.9	0.23	83.9	0.25	85.2	0.25	88	0.26	61	0.18
Sand and and river banks	1712	5.1	1822	5.4	1854	5.5	1887	5.6	1906	5.7	1799	5.4
Water bodies	670	2	520	1.5	500.7	1.5	488	1.5	514	1.5	581	1.7
Tea plantations	22.3	0.1	20.4	0.1	23.1	0.1	27	0.1	29	0.1	22.5	0.1
Total	33,485	100	33,485	100	33,485	100	33,485	100	33,485	100	33,485	100

Adapted from data presented by Rimal., B., Zhang, L., Stork, N., Sloan, S., Rijal, S., 2018. Urban expansion occurred at the expense of agricultural lands in the Tarai region of Nepal from 1989 to 2016. Sustainability 10, 1341. https://doi.org/10.3390/su10051341.

Table 3 Land cover and use changes during three periods between 1976 and 2000 in a mid-hill watershed in Nepal.

	1976		1989		2000		% change in land use		
Land cover/use	**Area (ha)**	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**	**1976–1989**	**1989–2000**	**1976–2000**
Broadleaf forests	4777.1	31.1	4967.1	32.4	5098.4	33.2	4.1	2.6	6.8
Conifer forests	567.9	3.7	819	5.3	1034.9	6.7	44.2	26.4	82.2
Shrublands	1318.9	8.6	711.3	4.6	1031.4	6.7	−46.1	45	−21.8
Grasslands	471.6	3.1	236.5	1.5	197.1	1.3	−49.8	−16.7	−58.2
Lowland agricultural areas	1578	10.3	2023.3	13.2	1834	11.9	28.2	−9.4	16.2
Upland agriculture and others	6627.4	43.2	6578	42.9	6139.4	40	−0.7	−6.7	−7.4

Adapted from data presented by Gautam, A.P., Webb, E.L., Shivakoti, G.P. Michael, A.Z., 2003. Land use dynamics and landscape change pattern in a Mountain watershed in Nepal. Agr. Ecosyst. Environ. 99, 83-96. https://doi.org/10.1016/S0167-8809(03)00148-8.

Table 4 Major land cover and use distribution by physiographic region in Nepal in 2010.

	Agricultural land area		Forest land area		Built-up land area		Barren land area		Lakes/rivers and snow/glaciers	
Physiographic region	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**	**Km^2**	**%**
High mountains	23	0.05	9667	13.03	1	0.22	13,105	83.59	12,062	93.19
Middle mountains	5286	12.04	24,148	32.55	3	0.55	488	3.12	178	1.38
Hill	19,783	45.05	22,621	30.5	200	42.69	269	1.72	206	1.59
Siwalik	4714	10.74	13,464	18.15	76	16.13	489	3.12	230	1.78
Terai	14,104	32.12	4280	5.77	189	40.33	1326	8.46	267	2.06
Total	43,910	100	74,180	100	469	100	15,678	100	12,944	100

Adapted from data presented by Uddin, K., Shrestha, H.L., Murthy, M.S.R., Bajracharya, B., Shrestha, B., Gilani, H., Pradhan, S., Dangol, B., 2015. Development of 2010 national land cover database for the Nepal. J. Environ. Manage. 148, 82-90. https://doi.org/10.1016/j.jenvman.2014.07.047.

High rates of farmland fragmentation and conversion to settlements and industrial uses are an increasing concern in South Asia and Nepal in particular (Niroula and Thapa, 2005). Paudel et al. (2013) reviewed the effects of previous land management policies adopted by the Government of Nepal on land fragmentation and land conversion.[a] Their analysis suggested that land use changes could be partly attributed to the failures of various old land management policies that aimed to control land fragmentation and land abandonment, and specifically those aimed at land re-distribution prior to new policies enacted in 2015 (MoLRM, 2015). The newer policies have provided a focus on more conventional regulation instruments aimed at limiting land fragmentation and agricultural land conversion to other uses. Examples of policy tools deployed to address these objectives include land pooling, land classification, zoning and tax or incentive-based discrimination to limit fragmentation and conversion from agricultural to other less productive land uses.

2.4.3 Farmers' perceptions of change

Paudel et al. (2019a) also assessed farmer perceptions of land use change and identified some of the major drivers of these changes. Their findings suggested the total amount of land devoted to agricultural uses in Nepal has expanded rapidly since 1910, with the greatest agricultural land conversion occurring in the Terai and central hills. Their work also suggested that conversion of land to agriculture has decreased slightly near cities in recent decades, supporting previous observations (Gautam et al., 2003; Rimal et al., 2018). Farmers' perceptions from a household survey of 530 households from 15 districts (five from the Terai; six from the hills, and four from the mountains revealed that the major drivers for modifications of agricultural land included increasing population growth (94%), improved road accessibility (77.4%), urbanization (33.8%), out-migration (79%), and agriculture and forest related government policies such as the Forest National Act of 1957 and the Land Ownership Registration Act of 1968 (23.6%).

[a] Policies reviewed include the Land Act 1964 Land Acquisition Act 1977, the Land Revenue Act 1977, the Agriculture Perspective Plan 1995–2015, the National Agriculture Policy 2004, the National Adaptation Program of Action 2010 and the National Land Use Policy 2012.

3. Environmental issues and challenges for cereal-based cropping systems in the terai and hills

3.1 Soil fertility

3.1.1 Soil characteristics and their distribution

A function of its physiography, Nepal is diverse in terms of soil and land characteristics (Haefele et al., 2014). Dijkshoorn and Huting (2009) identified 21 dominant soil groups across the five physiographies, with Cambisols occupying 35% of the country's area, and non-soils groups including rock outcrops and glaciers comprising an additional 20% of area. The remaining 45% is covered by Regosols, Leptosols, Gleysols, Luvisols, Phaeozems, Anthrosols, Fluvisols, and Arenosols. Based on the analysis of ~6000 soil samples across Terai, Inner Terai and hills, Bajracharya and Sherchand (2009) reported that about 60% and 35% of soils were low (less than 2.0%) and medium (2.0–4.0%) in organic matter, respectively. Similarly, about 50% and 40% of soils were low (less than 0.1%) and medium (0.1–0.2%) in total N. Contrary to soil organic matter (SOM) and total N, more than 60% samples had medium to high quantities of available P (greater than 50 ppm) and exchangeable K (greater than 50 ppm). The majority of soils were also identified as acidic (pH, less than 6.0). With exception of iron (Fe) and manganese (Mn), the contents of all other micronutrients tended to be low.

SOM varies with agroecological zones and is higher in hills and mountains. It is conversely lower in the soils of the Terai. Within the Terai, the eastern part of Nepal has lower SOM reserves compared to the western part. Total N, available P and K content varies widely. Most Terai and eastern mid-hill soils have total N content lower than 0.15%, while western mid-hill soils are rich in N. Similarly, P content of most eastern Terai soils is lower than 55 kg P_2O_5 ha^{-1}, but most western Terai soils are higher than 55 kg P_2O_5 ha^{-1}. Soils in the Terai have relatively lower K status than hill and mountain soils, in which K tends to fall within medium ranges (110–280 kg K_2O ha^{-1}). However, due to intensive crop cultivation coupled with residue removal from the farmland and lower use of organic inputs, K mining has started (Dawadi and Thapa 2015; Regmi et al., 2002a,b). In order to improve farmers' knowledge of their soil characteristics, the Nepal Soil Management Directorate recently started a soil-testing mobile van program to assist farmers to better understand how to manage their soils (Pandey et al., 2018b). Efforts however remain limited in scale.

In tropical environments and particularly in rice-based cropping systems, wet chemistry soil test results should also be interpreted cautiously as they may not always be a good proxy for responsiveness to fertilizer addition (Dobermann et al., 2003).

Soils vary in acidity and fertility across the agroecological zones. Turton et al. (1996) reported that one of the major contributing factors for declines in soil fertility and crop productivity in Nepal is soil acidification. Subsequent research by Tripathi (1999a) suggested that acid soils cover approximately 49% of Nepal's geographical area, while Bajracharya and Sherchand (2009) estimated that acid soils are around 55% of Nepal's area. Soil acidity in Nepal, is caused by presence of acid forming parent materials, leaching of calcium (Ca) and magnesium (Mg) resulting from intensive rainfall (85% of which is received from June–September), inappropriate use of acid forming chemical fertilizers, extraction of Ca and Mg by crops, and plantations of pine trees and use of pine litter as compost in crop fields (Tripathi, 1999a,b; Huang et al., 2015).

In general, the soils of eastern Nepal are relatively more acidic than in the central and western parts of the country. Similarly, soils in the hill and mountain regions are more acidic compared to the Terai. The soils of Terai, Inner Terai, mid-hills, and high hills are acidic to moderately alkaline, strongly acidic to neutral, strongly to slightly acidic, and neutral to slightly to strongly acidic, respectively. Slightly acidic soils have also been observed near homesteads of the mid- and high-hills; this is attributed to the repetitive addition of undecomposed farmyard manure and poorly processed compost in the lower-temperature environments of these regions compared to the Terai and Inner Terai (Paudyal et al., 2001; Timsina, 2001; Tiwari et al., 2004).

Contents of soil organic carbon (SOC), N, P and K are conversely lower at low elevation and increase with altitude in the hills, until temperatures at high elevation limit plant growth. Contents of Fe, Mn, and copper (Cu) appear to be largely sufficient, but boron (B) is deficient in all altitudes (Tripathi, 1999a, b). Rainfed uplands also generally have higher SOM and major and micronutrients than irrigated lowlands in the Terai. The base status of P and K conversely appears to be more influenced by geology and pedology than by anthropomorphic intervention (Bajracharya and Sherchand, 2009).

Digital soil maps can aid in decision making by agricultural development planners, policy makers, extension officers, and farmers in efforts to improve field-level soil fertility management (Sanchez et al., 2009). In Nepal, however, efforts to develop high-resolution maps are remains relatively nascent. A recent study in a limited geographical area used about 1500 samples from the hills and Terai revealed that mean SOM levels ranged from 0.01 to 1.77%, total N from 0.01 to 0.08%, mean available P_2O_5 from 16.5 to 197.8 kg ha^{-1}, and mean available K_2O from 84.3 to 422.6 kg ha^{-1} (Pandey et al., 2018b). Another study mapped the spatial distribution in soil chemical properties of the agricultural floodplain lands of the central Terai district Bara by combining soil sample data with a digital elevation model and using Kriging interpolation. The resulting map, which utilized 109 measured values, suggested moderate spatial variability for pH, SOM, N, P_2O_5, and a weak spatial variability for K_2O, zinc (Zn), and B, depending upon the use of soil amendments, fertilizing, manuring and tillage methods applied by farmers, in addition to the inherent characteristics of each soil parameter (Pandey et al., 2018a).

3.1.2 Synthetic fertilizer use

Compared to other South Asian countries, average fertilizer use application to cereal crops in Nepal is low. National mean rates of around 41, 18, and 18 kg of N, P_2O, and K_2O ha^{-1} have been observed (Takeshima et al., 2016), though use of fertilizer is highly heterogenous across crops, agroecological regions, and provinces. For example, observed fertilizer use in rice was 72, 21, 7 kg of elemental N, P_2O_5, K_2O ha^{-1}, while wheat averaged 86, 59, and 0.9 kg of N, P_2O_5 and K_2O ha^{-1} in six western Terai districts. The Terai is considered as Nepal's food basket (Puri et al., 2015), and thus has higher fertilizer use than in hills (CSISA, 2019; Devkota et al., 2018b; Hoyum, 2012; MoALD, 2018). These rates of fertilizer addition to these crops are however lower than the amounts farmers growing the same crops tend to apply in India and Bangladesh (CSISA, 2019). Moreover, the quality of fertilizer (particularly those imported through informal channels) used tends to be poor. This is in part because most of the fertilizers imported through informal sources come through Nepal's relatively open and porous border with India; only 14–30% of imported fertilizers are obtained through formal government-approved channels and have quality control standards (Hoyum, 2012).

Nepal's fertilizer markets also tend to be poorly developed as subsidized fertilizers are distributed primarily through farmer's cooperatives with limited involvement of the private sector (Hoyum, 2012; Takeshima et al., 2016; Takeshima, 2019). Moreover, farmers' knowledge on the importance of fertilizers including the right rate and timing of application is limited (Hoyum, 2012; Takeshima et al., 2016). Farmers generally do not apply fertilizers based on yield targets or an understanding of indigenous nutrient supplying capacity. Commercial soil or fertilizer nutrient testing facilities are underdeveloped; and in most cases, relatively sparsely located. Access to extension services and advisories on soil fertility management is also limited—with significant delays resulting from the current governmental process (Raut and Sitaula, 2012; Takeshima et al., 2016). As a result, many farmers apply fertilizers based on intuition rather than in consideration of inherent soil fertility, responsiveness to fertilizers, or yield targets.

One of the consequences of this situation is that when farmers do apply fertilizers, they tend to use relatively higher amounts of urea compared to phosphatic and potash fertilizers (Takeshima et al., 2016; NSAF, 2017). Federally sanctioned recommendations tend to not include detailed or regionally-specific advisories on the use of secondary and micronutrient fertilizers; as such, neither extension services nor farmers nor agricultural input retailers tend to have adequate awareness of the importance of micronutrients. Information on available sulfur (S), Ca and Mg are lacking. Most analyses are conducted to determine soil pH, OM, N, P, and K, with less work conducted on secondary and micronutrients (Andersen, 2007).

Since there is limited understanding of the importance of balanced fertilization for improving soil fertility and crop productivity, evidence indicates that farmers tend to prefer use of less costly fertilizers (e.g., urea) that show higher and more rapid crop response. Conversely, secondary nutrients (such as S, Ca, and Mg) and micro-nutrients including B and Zn, are far less considered, resulting in mining of soil nutrients (NSAF, 2019). This situation is problematic given that emerging evidence indicates that the soils in eastern Nepal contain lower amounts of Ca and Mg, which are associated with a higher rainfall regime compared to western Nepal, and are indicative of the need for regionally-specific fertilizer recommendations (Khadka et al., 2016a,b, 2019). In addition, a review by Bajracharya et al. (2007) suggested that soil micronutrients concentrations tended to decline as addition of organic inputs decreased with the intensification of cropping and over-reliance on synthetic fertilizers.

One plausible alterative to this dilemma is the use of improved organic matter management combined with the use of blended fertilizers (mixture of N, P, K with either B, Zn or S) based on crop and location-specific needs. Exempting DAP, there is currently no official import of blended fertilizers in Nepal, and although there is an interest in the manufacture of compound fertilizers, limited progress has been made (Kishore et al., 2019). Although the government of Nepal has registered some blended fertilizers including crop-specific blends for rice (NPK 20–20-20-1Zn), wheat (NPK 10–20–10-0.2B) and maize (NPK 10–20–20-0.3B), their field testing and validation—particularly under farmer management—remains lacking.

3.1.3 Organic matter amendments

Synthetic chemical fertilizers were introduced in Nepal in 1952 (Pandey and Joshy, 2000). Prior to this, manures and organic amendments were the major sources of nutrients in Nepal's agroecosystems. In these systems, plant nutrients are mostly supplied from organic inputs, including unprocessed or semi-processed farmyard manure (a mixture of animal dung, urine, and livestock bedding), composts, and crop residues, with limited use of cover crops (Sherchand, 1989; Timsina, 2001). Even today, many of the more remote farms in the hills and mountains are primarily reliant on organic amendments. In these environments, farmyard manure is often mixed with household wastes. The use of tree cuttings and forage from forest areas and grasses from terrace bunds used as animal feed are also common (Pilbeam et al., 2000). However, evidence indicates that the use of organic inputs is in a declining trend in Nepal (Bajracharya et al., 2007).

The decreasing trend in use of organic inputs has been associated with reduced densities of cattle, lower availability of forage or organic biomass for animal bedding, closure of community forests for fodder collection, in addition to increasing cropping intensity (Bajracharya and Sherchand, 2009; Paudel and Thapa, 2001). A relationship between tenure insecurity and soil fertility was also reported by Tamang (1991). A lack of security and short-term planning horizons mean that tenant farmers may be less willing to invest in fertilizer and organic matter inputs. A study conducted in Banke district of western Nepal showed that small and medium-sized farms used relatively higher amounts of organic inputs compared to large farmers (Baral et al., 2020). The higher amount of organic manures used by small and medium farmers ($\sim$12 Mg ha^{-1}) compared to large farmers ($\sim$6 Mg ha^{-1}) was associated with large numbers of cattle, small landholdings and shorter distances between farms and houses. Larger farmers had fewer cattle and longer distances from animal sheds to fields; as such, small amounts of organic manures were applied considering their relatively large cultivated area. The implications of these changes in organic matter use have important consequences for cropping systems over time.

Long-term experiments on rice-wheat systems conducted for 15 years in India and Nepal revealed that application of organic amendments can increase soil C and total N significantly as compared to the absence of organic matter addition (Tirol-Padre et al., 2007). However, the practice of preparation, storage and application of farmyard manure and compost is often less optimally managed than it could be. Organic matter is rarely systematically composted or stored; rather, materials tends to be left in the open and not incorporated soon after application, which can result in the loss of N to volatilization (Maskey et al., 2000a,b). Beyond livestock, other sources of organic amendments include poultry and hog manures, compost prepared from crop residues and other farm wastes, vermiculture, oil cakes, and biological wastes such as animal bones and slaughterhouse refuse. Bhattarai (2011) recently estimated that there were 58 million broilers, 6 million layers and 1 million parent birds in Nepal. In aggregate, these birds produce about 0.3 million tons of dry poultry manure annually. As poultry manure has approximately 4% N (Adhikari and Dahal, 2015), the total amount of N derived from poultry manure not considering losses amounts to approximately 12,000 tons yr^{-1}. Poultry rearing facilities however may not always be located proximally to farms, and a lack of adequate transport facilities and labor for manure application remain constraints to the wide-scale use of poultry and other manures. Residues derived from crop products in Nepal have conversely been estimated to be roughly on the order of 2.5 million tons yr^{-1} (Khatiwada et al. 2013; Pokhrel and Virarahghavan, 2005), though proportions of C, N, and lignin contents vary considerably among sources of plant residues.

3.1.4 Biological nitrogen fixation

Common sources of biological nitrogen fixation (BNF) in Nepal's cereal-based farming systems include *Rhizobium* spp. associated with legumes and *Azotobacter* spp. associated with blue-green algae (*Anabaena azollae*), primarily in rice paddies (Adhikari and Dahal, 2015). Although these sources of BNF are relatively common in Nepal, they tend to be less optimally managed than they could be, and are more a fixture of less intensive farming systems than purposefully integrated to reduce reliance on synthetic sources of N. When optimally managed, BNF can however make a meaningful contribution to farming systems productivity when pulses are grown independently or in rotation with cereals. Results of multi-location trials for example showed that the application of *Rhizobium* spp. as an inoculant for legumes increased the grain yield of soybean by 62%, lentil by 25%, black gram (*Vigna mungo*) by 49% and peanut (*Arachis hypogaea*) by 34% (Maskey et al., 2000a,b). The effectiveness of *R. japonicum* in particular increased soybean yield by 32–45% relative to plots without inoculants or nutrient amendments in multi-locational trials (Bhattarai and Maskey, 1988).

Seed treated with different strains of *Rhizobium* had a positive effect particularly on lentil yield, with the greatest increment of 533 kg ha^{-1} observed for seed treated with *R. leguminosarum* in Khumaltar, located in Nepal's mid-hills. Inoculation of lentil with different strains of *Rhizobium* was also shown to have a greater yield response than application of 50 kg N ha^{-1} in the form of urea at sowing (Soil Science Division, 1999). No effects were however observed at the high-altitude location of Jumla, located above 2500 m (ARS, 1994). Conversely, inoculation with the 'Mainapokhari' strain of *Rhizobium* in Dolakha district, located between 1000 and 2000 m, produced the highest lentil yield at 1342 kg ha^{-1} followed by the strain TUL-311 (1299 kg ha^{-1}) in the Inner Terai district of Surkhet at 300–1000 m.

Attempts to quantify BNF in on-farm environments in Nepal are relatively rare. Work conducted in the mid- to late-1990s showed that for winter and summer legume crops in the hills and Terai regions, the proportion of legume N derived from N_2 fixation in summer crops ranged from 46% for black gram to 62% for soybean, while for the main winter pulses, BNF contributed 77–80%. The same study observed relatively similar rates of BNF in farmers' fields and research station soils (Maskey et al., 2000a,b). Indigenous isolates of carrier-based *R. japonicum* from 12 soybean varieties revealed soybean yield increase by 24.4, 23.7, 22.1, 20.2, 20.2, 18.6 and 17.4% in varieties THA7, PK7394, Ransom, KS419X, KS525, Sathia local and 79W330, respectively. Increases in root nodule number and dry weight were also observed (Bhattarai and Shrestha, 1990). Yield increases in soybean with the addition of *R. japonicum* inoculant was also found to be superior to the yield obtained with extension recommended doses of synthetic fertilizers (at 50:40:30 kg N:P_2O_5:K_2O ha^{-1}). Considering differing methods of inoculation, liquid and carrier based *R. japonicum* application alongside three strains of *Rhizobium* (SMB 5001, 5002, 5003) isolates found in cowpea varieties CES41-6, 23F-780-3 and IT082D-755 showed a clear response to inoculation (Soil Science Division, 1992). These benefits can also extend on a cropping systems basis. Bhattarai (1987) for example conducted field and green house experiments at Khumaltar in the mid-hills; in a rice-pulse rotation they showed a 17% increase in rice yield when *Rhizobium* was supplied to pulses.

Azolla spp. is a free-floating water fern common in South Asia. When associated with blue-green algae, *Azolla* spp. can fix 40 to 60 kg N ha^{-1} from atmospheric N_2. Under optimal conditions, *Azolla* spp. can release as much as 70% of fixed N to the rice crop upon incorporation, providing a slow-release source of N in lowland rice fields (Kannaiyan, 1982). *Azolla* spp. can also be harvested from rice paddies and used as a supplement in compost. Bhattarai (1987) observed that crop productivity could be improved when *Azolla* spp. were incorporated into compost and applied to wheat, chili (*Capsicum* spp.), and potato. Finally, *Azotobacter* spp. is a free-living diazotrophic bacteria. Isolating and applying *Azotobacter* spp. to maize, Sherchand (1989) reported a small yield increment of 24 kg ha^{-1}. They also studied the effect of *Azotobacter* spp. addition to wheat, and observed 12–21% yield increases with the varieties Lerma 52 and RR 21 relative to control. Wheat response to *Azotobacter* inoculation in combination with farmyard manure addition was also found to be positive under high altitude conditions in Jumla (ARS, 1981).

3.2 Climate and cereal-based farming systems

The climate of Nepal varies considerably, with elevation playing a strong driving role. Nepal's climate can be broadly classified as cold Arctic or Nival (at altitudes above 3000 m), cold temperate (2000–3000 m), warm temperate (1500–2000 m), subtropical (1000–1500 m) and tropical (less than 1000 m) (Gaire and Subedi, 2011). Paudyal et al. (2001) reported that the average temperatures in the mid-hills are 5–8 °C lower than the Terai, and 3–8 °C higher than the high-hills. Crops develop more rapidly and mature earlier in the Terai compared to the mid- and high-hills because of higher average temperatures than in hills. Summer rain typically occurs in June or July, with the monsoon onset date varying across a west-east gradient, and varying by agro-ecological zone. Of the total precipitation received annually in Nepal, the monsoon season (June to September) accounts for approximately 80% of total annual rainfall (Sigdel and Ikeda, 2012).The hills of the eastern and central regions receive rainfall summer monsoon rainfall approximately 2–4 weeks before the western Terai and rest of the mid- and high-hills (Paudyal et al., 2001). The far-western Terai and hill regions, however, receive more rainfall than other regions in the winter season, which tends to span from mid-November through April.

3.2.1 Climate change

This study adopts the IPPC (2007) definition of climate change, indicative of the change in climate state that can be isolated and identified through changes in the degree of variability or mean of climatic properties and variables that persist for an extended period, typically 20 or more years. Despite availability of good body of literature on climate change in Nepal (Bharati et al., 2016; Budhathoki et al., 2020; Lamichhane and Shakya, 2019; Pandey et al., 2019, 2020; Shrestha et al., 2020), studies related to impact of climate change and variability on crop productivity, profitability and environmental consequences are still somewhat limited.

Increases in temperature under climate change could amplify adverse impacts on food production (Reynolds et al., 2016)—and also potentially storage and distribution of grain—thereby adding pressure to efforts to increase achieve self sufficiency in domestic production. Temperature thresholds for heat stress vary according to crop species and phenology, as well as timing, duration and intensity of stress. For cereals there are generally two stages that are most sensitive to temperature. The first is approximately a week prior to anthesis, leading losses in pollen grain formation and release. The second is at fertilization. Stress during this period can result in decreased pollen shed, pollen reception on stigma, and pollen tube growth, resulting in reduced fertilization rates and early embryo abortion (Lobell and Field, 2007; Reynolds et al., 2016). The implications of potential changes in temperature and other variables under climate change and crop productivity are most widely assed using integrated crop and climate modeling efforts.

General circulation models (GCMs) are widely used globally to project possible future climates. Using 13 GCMs, APN (2005) projected an increase in average annual temperature of 2.47 °C and 4.29 °C with respect to 1971–2005 baseline, in 2050 and 2080, respectively, with large increases during the winter dry season (2.89 °C and 4.96 °C, respectively), compared to the summer season (2.09 °C and 3.67 °C, respectively). Furthermore, projected increases in temperature are lower in eastern Nepal compared to the country's central or western region.

Such location-specific effects will have both positive and negative consequences on crop yields (Bannayan et al., 2011; Hossain et al., 2018; Kukal and Irmak, 2018; Paudel, 2016a,b). Modeling efforts suggest that increased temperatures may have negative impacts on yields of all cereals in the Terai, but positive impacts on rice and maize in high-elevation areas in the mid-hills of the Koshi River Basin (Bhatta et al., 2014). Depending on location and elevation, crop yield response to a unitary increment in growing season mean temperature varied in the range of −6 to 16%, −4 to 11% and − 12 to 3% respectively for rice, maize and wheat, although this study did not account for the potential effects of CO_2 fertilization. APN (2005) used the DSSAT-CERES models to simulate rice, wheat and maize under climatic change and elevated CO_2 concentrations. Model predictions showed that compared to the baseline levels (382 ppm CO_2 concentration with current temperatures and under rainfed conditions), rice yield increased by 9.5% in the Terai, 5.9% in the hills and 16.6% in the mountains with elevated

CO_2 (+250 ppm). Percent changes however were reduced to 3.4% in the Terai, increased further to 17.9% in the hills and to 36.1% in the mountains with the combined effect of elevated CO_2 and temperature rise. Changes in yield conversely dropped to −0.8% in the Terai and to 14.6% in the hills, but increased by 39.1% in the mountains with combined effect of elevated CO_2, temperature rise and 20% increased in rainfall. Wheat yield rose by 41.5% in the Terai, 24.4% in the hills and 21.2% in the mountains under elevated CO_2 only. Combining elevated CO_2 with a 4 °C temperature increase, wheat yield rose in mountains and hills, but dropped in Terai. Simulation of an additional 20% more seasonal rainfall had an additional positive impacts on wheat yield in Nepal's mountains at all levels of temperature rise. Considering maize, elevated CO_2 alone had a relatively small effect, with simulated yield increases of 9.0% in the Terai, 4.9% in the hills and 15.5% in the mountains. When combined with a temperature increase, maize yield declined in the Terai and hills to 26.4% and 9.3%, respectively, below baseline levels. These changes were not countered significantly by simulations of increased rainfall, with no effect of increased precipitation on maize yield in the Terai and hills, though significant and positive impacts were observed in the mountains. In summary DSSAT-CERES model predictions revealed that Nepal's high elevation cereal-based farming systems are most likely to benefit positively from climate change, while both the hills and Terai are likely to suffer. Bhatta et al. (2014) also investigated climate–crop yield relationships and the impact of historical climatologies on rice, maize and wheat yields in the Koshi River Basin in eastern Nepal. In partial confirmation of modeling efforts, findings suggested that when rice, wheat, and maize are cultivated at altitudes below 1100 m, 1350 m, and 1700 m, respectively, they suffered high temperature stress, particularly during and after anthesis.

Employing a stochastic production functional model, Poudel et al. (2014) used district panel crop data collected by the Ministry of Agriculture and climate data for 20 years (1990–2010) by the Department of Hydrology and Meteorology (DHM) for 12 districts representing all three agroecological zones of Nepal. Their results vary to some extent with from Bhatta et al. (2014) and APN (2005). They observed that an increase in maximum temperature by 1 °C would decrease maize yield by 23.6 kg ha^{-1} yr^{-1}, increase wheat yield in the hills by 44.9 kg ha^{-1} yr^{-1}, but with no effect on rice yield. Increased minimum temperature by 1 °C, however, increased rice, maize and wheat yields by 68, 7 and 56 kg ha^{-1} yr^{-1}, respectively. This effort however did not account for CO_2 enrichment. In addition, increases in yield are unlikely to come without additional trade-offs: increased maximum temperatures were reported to potentially increase variability in rice and maize but not for wheat yields, while increased minimum temperatures would decrease yield variability in all crops. Aside these points, high maximum temperatures coupled with extremely low rainfall would significantly reduce yields of all crops. Extreme minimum temperatures for rice, maize and wheat were 8.2, 6.3 and −3.5 °C, and extreme maximum temperatures were 33.6, 34.6 and 30.4 °C, respectively. Extreme minimum precipitation amounts, respectively, were 478, 1160 and 0 mm, while extreme maximum precipitation amounts were 4348, 4682 and 535 mm respectively.

Palazzoli et al. (2015) investigated the effect of projected climate change in 2100 on hydrology and cereal yields in the Indrawati River Basin in central-eastern Nepal. Climate scenarios from three GCMs (CCSM4, EC-Earth and ECHAM6), each simulated using three representative concentration pathways (RCPs), were fed into Soil and Water Assessment Tool (SWAT) to estimate hydrological fluxes and changes in crop yield during 2045–2054 and 2085–2094, compared to those observed from 1995 to 2004. SWAT requires surface water stream flow data for its calibration and validation. Several hydrological response units (i.e., grouped areas displaying unique land cover, soil, slope and management conditions) were developed in this study. Hydrological fluxes were mainly determined by precipitation, with less influence from snow and glacier cover. Hence, projected yields resulting from the integration of the climate and SWAT models were based on precipitation and surface hydrology occurring in the catchment, together with changes in temperature patterns. Their results showed annual changes in surface hydrological fluxes (−26% to +37%) and yields (−36% to +18% for wheat, −17% to +4% for maize, and − 17% to +12% for rice). Wheat was more vulnerable to climate change than maize. Rice and wheat yield response to climate change also varied with altitude.

Investigating potential adaptation approaches to climate change, Bocchiola et al. (2019) used a hydrologically based, multi-year daily Poly Crop model (Nana et al., 2014), to investigate whether the elevational extension of areas under rainfed cereals in the Dudh Koshi River Basin at the foot of Mount Everest could increase productivity and improve food security (measured as the ratio of caloric content of these cereals to daily caloric intake) within the basin. Their results suggested a projected decrease in average yields of rainfed wheat, rice and maize by −25%, −42% and − 46%, respectively, in 2100 compared to 2003–2013, with large inter-annual variability. These findings imply that growing rainfed wheat in high altitudes in locations where consistent supply of supplemental irrigation is possible from

February to April could assist in maintaining present yield conditions, even under climate change. Rice yield under rainfed conditions could also be increased at higher altitudes by providing supplemental irrigation during April to June. Although maize yield in general would decrease with much larger inter-annual variability than during the 2002–2013 period, modeling efforts conducted by Bocchiola et al. (2019) suggest maize cropping at higher altitudes could result in slight yield increases, though it would also require supplemental irrigation during the spring.

The findings of Bocchiola et al. (2019) and Palazzoli et al. (2015) suggest that climate change in the near and mid-term future could negatively affect food security in the Dudh Koshi and Indrawati catchments, which are likely to be analogous to other high-altitude areas of Nepal. The hilly and mountainous regions of Nepal have enormously varied topography and have been described as climate change vulnerable—in particular due to their remote nature and lack of easy access to markets and services that could help improve adaptability to climate change. These factors render these environments and cereal-based farming systems particularly susceptible to climate change. These findings also have implications to similar basins and agro-ecologies in other countries of the Himalayan region of South Asia, for example those in adjacent areas of India, Pakistan, and Bhutan.

3.2.2 Rainfall variability

Rainfall variability is one of the critical factors governing farming systems and affecting flood regimes in South Asia. As reported by Poudel et al. (2014) using a stochastic production functional model, an increase in precipitation by one standard deviation from the longer term average (1990–2010) could decrease summer maize yield, but could conversely increase rice and wheat yields and reduce their variability, across 12 districts representing all three agroecological zones. The onset, strength, and consistency of the rain occurring in South Asia's mono-modal monsoon period greatly affects soil water availability to crops, planting and harvesting times, and can pose crop production at risks (Selvaraju et al., 2014; Aryal et al., 2019). Sapkota and Devkota (2019) provided a summary of climate trends and climate change effects on future cereal yields, while also discussing farm-level adaptation strategies. Building on this effort, our analysis of long-term rainfall data (43 years) from eight Terai districts (Sunsari, Dhanusha, Bara, Chitwan, Rupandehi, Dang, Banke, Kanchanpur) from 74 meteorological stations as recorded by the DHM suggest that national average annual rainfall has decreased by 172 mm (4.0 mm yr^{-1}) (DHM, 2018) (Fig. 11). In comparison,

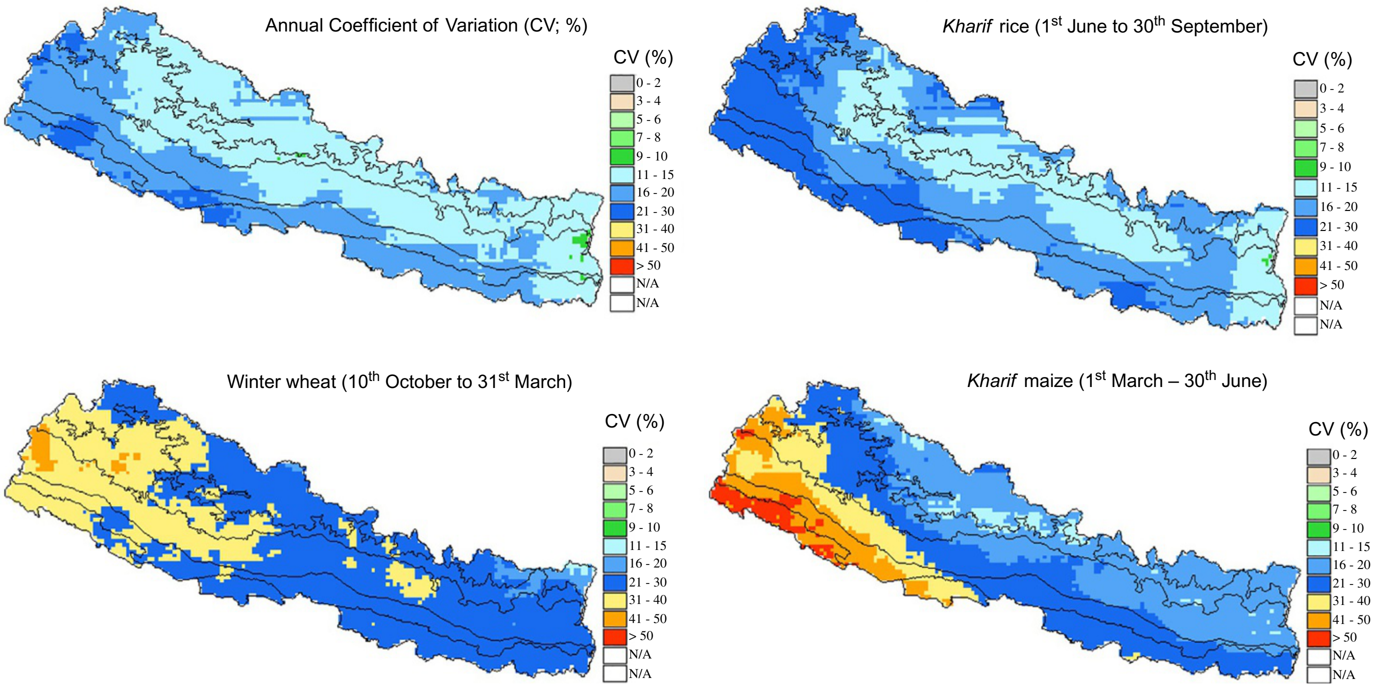

Fig. 11 Rainfall variability (coefficient of variation, %) in Nepal (1st row left), during rice growing season (1st June to 30th September; 1st row right), during wheat growing season (10th October to 31st March; 2nd row left), and during maize growing season (1st March to 30th June; 2nd row right) during 1982–2016. Derived from CHIRPS rainfall reanalysis including all metrological stations of Nepal.

a national study by the DHM showed that average rainfall across the country decreased by 1.33 mm yr^{-1}, with greater decreases in the mountains than other areas (−3.17 mm yr^{-1}) and during the early post-monsoon season (−0.32 mm yr^{-1}) (DHM, 2017). These findings suggest that high-altitude mountainous areas are more sensitive to climate change compared to the lower-altitude Terai and mid-hill areas.

Our long-term rainfall data from 1975 to 2015 (40 years) in 18 Terai districts also showed a 27% probability of drought during the predominant summer rice growing period, which appears to be associated with a 25% yield reduction. Rainfall variability has a clear negative correlation with rice yield (Fig. 12). Drought probability was calculated by dividing the number of drought years by the total number of years in the data. A year was considered to have sustained a drought if rainfall in that year is less than 80% of the long-term average (cf. Pandey et al., 2007). Climate Hazards Infrared Precipitation with Stations (CHIRPS) is a semi-global precipitation dataset, which can assist researchers to examine rainfall patterns and deficits and environmental change over land (Funk et al., 2015). Our analysis of CHIRPS gridded precipitation data, which are constructed from observed meteorological stations data and are available in Nepal, supplemented by 0.05° CHIRPS infrared resolution satellite imagery data from 1982 to 2016 suggested a yearly rainfall variability of 2–30% and a variability of 16–30% for the vegetative to early reproductive period of summer rice (1 June to 30 September). Rainfall variability of 21–40% was observed during the

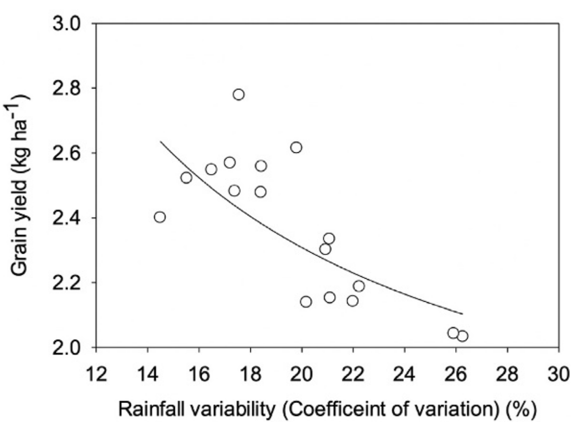

Fig. 12 Rice yield response to rainfall variability during the months of June–October from the long-term rainfall data from 1975 to 2015 in 18 Terai districts of Nepal. *Courtesy of the Department of Hydrometeorology.*

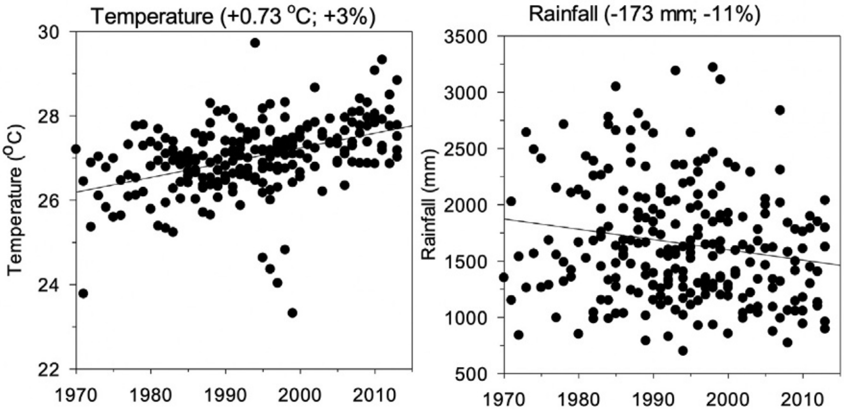

Fig. 13 Change in temperature and rainfall compared to the base years 1970–80 to 2003–2013 in eight Terai districts. *Data extracted and extrapolated from Department of Hydrometeorology stations in Sunsari, Dhanusha, Bara, Chitwan, Rupandehi, Dang, Banke, Kanchanpur over 43 years.*

dry winter season growing period (10 October to 31 March), and 21–50% during the early maize growing period (1 March to 30 June). Rainfall variability varied widely among the Terai, hills and mountains, and from the east to west (Fig. 13). During the key growing periods for Nepal's three major cereal crops, our analysis of CHIRPS data indicates that western Terai has the highest rainfall variability.

3.2.3 Farmer perceptions of climate change and variability

At a national level of analysis, and using a multi-household Computable General Equilibrium (CGE) model, Chalise et al. (2017) concluded that depending on severity, climate change could reduce household income by 10–14%, decrease GDP by 3–10%, and could have a significant and negative effect on the Nepalese economy. These effects would be more pronounced for resource-poor and subsistence farmers. Through farmer surveys, Khanal et al. (2018) identified the factors influencing farmer" decision-making for adoption of climate change adaptation strategies and the ways such strategies could impact farm productivity. Their findings revealed that farmers' level of education, access to credit and extension services, prior experience coping with the impacts of extreme events, information and knowledge on climate change, and farmers' personal and spiritual beliefs influenced their decision-making and interest in climate change adaptation strategies. These findings suggest that local famers' knowledge, perceptions, and views should be considered in planning and formulating adaptation strategies. Failure to do so is likely to result in the development of inappropriate adaptation policy, resulting in lower than desirable rates of adoption. For example, considering the importance of socio-economic and cultural factors on the understanding of, and willingness to adapt to climate change, Ensor et al. (2019) argued that adaptation strategies based on bio-physical impact-oriented epistemology alone would fail. Rather, approaches based on the understanding of how socio-economic and cultural changes are both influenced by, and how they influence environmental stresses, is needed for appropriate adaptation strategy formulation.

3.2.4 Changes in hydrology

Rainfall change and variability can affect crop production in various ways, which include but are not limited to, affecting soil moisture storage, irrigation water availability, irrigation water demand, and cultivation, among others (Doll, 2002; Hasan et al., 2019; Panda et al., 2019). Rainfall variability can affect water availability and subsequent maintenance of streamflow for irrigation water supply (Pandey et al., 2019, 2020). Almost all climate change studies simulate the combined impact of both rainfall and temperature variability together; this is because surface flux in the river is a function of both, therefore, it is difficult to quantify contribution of rainfall variability alone on total streamflow changes. However, due to the relationship between rainfall and runoff, rainfall variability can be considered as a prime factor affecting changes in water availability. Rainfall variability also affects groundwater recharge and subsequent availability (Nyakundi et al., 2015), with implications for irrigation and other uses. This arises from reduced residence time availability for more frequent but highly intense rainfall which allows less water to infiltrate and reach to groundwater aquifers.

Pandey et al. (2020) applied the Soil and Water Assessment Tool (SWAT) in the Karnali-Mohana river basin and projected increase in surface water resources by 6.4% under RCP4.5 at Chisapani hydrological station (index = Q280). Wide variation across the sub-basins as well as across months, for example, from −10.6% (in June) to 47.3% (in April) was also observed in the future. Similarly, Bharati et al. (2014) projected decrease in pre-monsoon surface water volume by 16% under A2 emission scenarios by 2050s in the Koshi Basin. Glaciers, which feed large perennial river systems in Nepal, are also shrinking, as indicated in the Langtang Himalayas by Chaulagain (2009). This study found that only 24% of the current glacier-ice reserve will be left by the end of this century if current glacier melting rates continue. These studies indicate that snow-fed river systems are more sensitive to climate change and variability, and as such by inflows to irrigation systems that divert water from those rivers are likely to be altered by changes in precipitation. Temperature rise and subsequent melting of snow could in turn be beneficial in the near future due to more water availability during the dry season; however, in the long-run, when snow cover depletes, this will lead towards longer-term water scarcity (Pandey et al., 2019).

Irrigation for small-holder farms in Nepal's hills and higher altitudes are dependent upon spring flows, which are more sensitive to development activities than climate change and variability. With including haphazard road and urban construction, and subsequent obstruction of spring flow paths, drying trends are on rise (Paudel and Duex, 2017). This leaves agricultural production as well as livelihoods at risk. The process of making limited water reserves in streams and springs available to farms is however hindered by topographical challenges and ensuring equal access to water resources, the latter of which are strongly affected by socioeconomic factors, including caste power dynamics (Pariyar et al., 2018).

3.3 Land degradation and management

3.3.1 Erosion and nutrient losses

Our review of the literature indicates that deforestation and land use changes result in increased soil erosion, runoff, and nutrient losses from the upland terraces in steep hills and mountains. Research by Chalise et al. (2019) indicated that 2.22, 0.65 and 0.29 million ha of forest, rangelands, and agricultural land on sloping terraces in Nepal are degraded. Annual soil erosion rates from agricultural land could be as high as 2.7–35 $t\,ha^{-1}\,yr^{-1}$ (Gardner and Gerrard, 2003; Partap and Watson, 1994; Schreier et al., 1998; Sherchand and Gurung, 1995). Consequent SOM and soil N, P, and K losses could be up to 150–600, 7.5–30, 5–25 and 10–40 $kg\,ha^{-1}\,yr^{-1}$, respectively (Brown and Shrestha, 2000; Partap and Watson, 1994), although there appear to be relatively few recent studies confirming these early results. Multiple cropping can expand the periods of the year during which the soil is partially protected by a standing crop canopy, which can in turn aid in reducing soil and nutrient losses from erosion events (Bashagaluke et al., 2018; Paudel, 2016a,b). Yield and economic benefits have been reported if appropriate terracing and tillage practices, or intercropping configurations are used (Paudel, 2016a,b). On contrary, Atreya et al. (2005) reported that mixed cropping (another common type of multiple cropping that can be observed especially in the hills) of maize and soybean (*Glycine* max*)* did not reduce soil and nutrient losses compared to the monocropping of maize followed by fallows in the central mid-hills (1500 m; 18% slope) of the Kathmandu valley.

Over time, terraces in the mid- and high-hills can become degraded when placed on steep slopes, in areas with high rainfall intensity, and where farmers cultivate high nutrient extracting crops without sufficient nutrient replenishment. In particular, decreased use of farmyard manure or compost, or increased use of acid forming chemical fertilizers without mitigating measures have been reported as sources of land degradation (Acharya et al., 2007; Gardner and Gerrard, 2003). Nutrient balance calculations suggest that integrated nutrient management with residue incorporation or retention, and appropriate use of farmyard manure supplemented by chemical fertilizer application can benefit soil fertility and farm productivity in the mid-hills (Tiwari et al., 2009a). Reduced labor availability due to out-migration may however present challenges for the transfer of manure from sheds—where animals are most commonly kept in the mid- and high-hills—to fields.

In addition to physical degradation, erosion in Nepal's uplands can also lead to nutrient losses. Acharya et al. (2007) and Gardner et al. (2000) demonstrated that losses of NO_3-N and K through leaching (45 and 180 kg ha^{-1} yr^{-1} respectively) in the mid-hills tended to be larger than through soil erosion and runoff. Tiwari et al. (2009b) reported that soil and nutrient losses through runoff and sediment from unbunded rainfed upland terraces are also significantly higher during the pre-monsoon season than peak or post-monsoon season (Table 5). A possible explanation for these observations is the higher soil loss and greater nutrient concentrations in sampled

Table 5 Seasonal average nutrient losses from experimental plots through runoff and sediments.

Nutrient	Pre-monsoon season (kg ha^{-1} yr^{-1} ± SE)	Peak-monsoon season (kg ha^{-1} yr^{-1} ± SE)	Post-monsoon season (kg ha^{-1} yr^{-1} ± SE)
Runoff			
Mean NH_4-N + NO_3-N	0.64a ± 0.1	0.40b ± 0.1	0.68a ± 0.1
Mean PO_4-N	0.02b ± 0.0	0.06b ± 0.0	0.11a ± 0.02
Sediments			
Soil organic carbon	21.5a ± 3.4	4.1c ± 0.7	9.1b ± 0.8
Total N	4.8a ± 0.8	0.8c ± 0.2	2.1b ± 0.2
Average P	0.03a ± 0.0	0.01b ± 0.0	0.01b ± 0.0
Exchangeable K	0.08a ± 0.0	0.02c ± 0.0	0.04b ± 0.0

SE indicates standard error.

Adapted from data presented by Tiwari, K.R., Sitaula, B.K., Børresen, T., 2009a. Effects of soil and crop management practices on yields, income and nutrients losses from upland farming systems in the Middle mountains region of Nepal. Nutr. Cycl. Agroecosys. 12, 26-41. https://doi.org/10.1007/s10705-009-9289-0.

runoff water and eroded sediment during pre-monsoon season, while the nutrient loss during the peak- and post-monsoon tended to be lower, potentially due to lower sediment losses and low soil nutrient concentrations resulting from less unexposed cropland soils, and also due to plant uptake. Even low to medium-sized rain events (27–39.4 mm day^{-1}) and kinetic energy intensities (39.4–192.8 MJ ha^{-1} mm^{-1} h^{-1}) in the pre-monsoon season resulted in higher soil and nutrients losses compared to the of the peak-monsoon season (46–53 mm and 104.2–404.2 MJ ha^{-1} mm^{-1} h^{-1}, respectively) (Tiwari et al., 2009b). Using a soil erosion assessment model, Shrestha (1997) showed that annual soil loss rates were up to 56 t ha^{-1} yr^{-1} on sloping terraced lands with rainfed cropping, while they were less than 1 t ha^{-1} yr^{-1} under dense native forest cover. Studying a mid-hill watershed in central Nepal, Tiwari et al. (2008b) also observed that 61% of the average annual rainfall (1202 mm) resulted in significant soil erosion, with as much as 60% occurring as a result of just one or two major storm events during the pre-monsoon period, when soils were either bare or freshly tilled. Soil loss from agricultural land (1.3 t ha^{-1} yr^{-1}) was also higher than from community managed forest land (0.3 t ha^{-1} yr^{-1}).

3.3.2 Indigenous knowledge of soils and associated management

Desbiez et al. (2004) reported that farmers in the mid-hills of western Nepal used various indicators to evaluate and monitor soil fertility of their fields. Their results showed good agreement between farmers' soil fertility assessments based on criteria including soil color compared to soil chemical analysis. In addition to soil physical and chemical properties, farmers also evaluated soil fertility on functional criteria, such as weed seed bank abundance. For this reason, Desbiez et al. (2004) suggested that farmers' perceptions of soil fertility could be described as more holistic than those of soil scientists. Tripathi and Jones (2010) also suggested that farmers' knowledge of soil fertility should be incorporated in the development of improved soil fertility management programs for hill-based farming systems. In this study, farmers emphasized that altitude, land types, aspect, soil color and texture can have a strong influence on indigenous soil nutrient supplying capacity to the crop. Lastly, Pandit and Balla (2006) analyzed farmers' perceptions and assessments of soil fertility management in the Pokhare Khola Watershed in mid-hills in the center of Nepal. Farmers suggested that soil erosion in uplands and sedimentation in irrigated lowland terraces were major threats to soil fertility.

In the mid-hill districts of western Nepal, Paudel and Thapa (2001) also observed that farmers in the hills are well aware of the issues of land degradation. Farmers at even higher elevations in Nepal's mountains who practice integrated crop-livestock-tree based farming systems in terraced lands acquire and use their indigenous skills, knowledge and techniques in farming, which have also maintained agricultural biodiversity (Paudel and Thapa, 2001; Timsina, 2001). Farmers therefore innovate and have a rich history of developing indigenous land use practices including structural and biological measures to improve land management (e.g., terraces and terrace bunds, diversion and productive use of waterways, construction of retention walls, and alley cropping, green manuring, and mulching to reduce soil run-off in addition to soil fertility maintenance).

3.3.3 Land terracing

Poorly implemented and unsustainable land use and land management practices can result in soil and land degradation, and soil, water and nutrient losses in Nepal's hills and mountainous areas. Appropriate soil and land management practices are therefore necessary to arrest and slow down the degradation processes on sloping lands that are used for agricultural production. Land terracing, a land management practice that involves land leveling and bunding in a stepwise fashion on hill slopes, is widely used as an indigenous practice to reduce land degradation and soil, water and nutrient losses in hilly and mountainous environments (Tarolli et al., 2014). Terracing is common in the hills and mountains of Asia, Africa, and South and Central America. On the sloping terrain of hills and mountains, farmers construct terraces of varying widths, lengths and heights, often 2–3 m wide and 50–80 m long. These are used to grow crops, vegetables, fruits and trees, and raise livestock (Chapagain and Raizada, 2017). Terraces can be carefully leveled and bunded to accumulate water for rice cultivation, or sloping or un-bunded to grow non-rice crops. However, terraces also come with a caveat: terraces require regular maintenance, and when abandoned, they can collapse and/or result in gully erosion (Tarolli et al., 2014).

3.4 Crop intensification, ecosystem services and environmental quality

Environmental quality and the flow of ecosystem services both to and from agricultural systems are affected as farmers include more crops per unit of land within annual production cycles (Rasmussen et al., 2018). Green revolution technologies such as irrigation, improved crop varieties, and fertilizers have helped increase crop intensification in Nepal, particularly in the low-lying and irrigable land tracts of the Nepal Terai. These technologies have now also begun to spread—though heterogeneously and at a limited scale—into Nepal's mid-hills. Pandit and Balla (2006) reported that use of early-maturing crop varieties supplemented with use of chemical fertilizers had substantially increased crop intensification in the irrigated lowlands of the Terai and mid-hills of the central region, respectively. Tiwari et al. (2008a) also showed that adoption of vegetable-based intensive cropping systems could improve the socio-economic circumstances of upland farmers, particularly the poor, women, and disadvantaged groups. This analysis considered primarily food security, farm income, resource accessibility, employment opportunity, and social status, with less emphasis on environmental outcomes. In general, vegetable farming (especially during the winter 'off-season') is more profitable than growing cereals, however, the availability of irrigation water, farmers' skills for off-season production, ability to effectively negotiate for adequate prices and access to markets, in addition to storage facilities, are limiting. In the mid-hills of Nepal, crop intensification has also provided employment opportunities where out-migration is more common, thereby providing pathways to income generation and the ability of families to procure additional food products and maintain food security (Tiwari et al., 2008a; Raut et al., 2010). These developments however have not come without negative consequences. Dahal et al. (2009) analyzed farmers' perceptions of the effects of agricultural intensification on society and the environment in the Ansikhola Watershed of Kavre district. The study concluded that market-oriented intensive vegetable-based production systems improved the socio-economic conditions of farmers, although not without environmental consequences resulting from increased use of pesticides.

Crop intensification has also been associated with increased infestation of soil nematodes. Culman et al. (2006) investigated the effect of soil solarization applied to the nurseries and main fields of rice on the incidence of nematodes and on crop yields, under an intensive rice-wheat rotation at two locations in Nepal. Their results demonstrated that solarization in the main field increased fungal propagule counts, decreased root galling and nematode counts, and also decreased weed biomass. Solarization however failed to increase crop yields at either location. Likewise, solarization has been shown elsewhere to reduce nematodes and increased crop yields under intensive cropping systems (Timsina and Connor, 2001).

Additional research on the implications of crop intensification has focused on greenhouse gas emissions. Raut et al. (2010,2011) for example suggested that intensification in the mid-hills was likely to be associated with land degradation and increased emissions of N_2O, challenges which they commented are best addressed not only with appropriate agricultural technologies, but also with efforts to increase farmers' understanding on the importance of resource conservation and ecosystem services, in addition to local institutions to regulate the potentially harmful environmental effects of intensification practices. Acharya et al. (2007) and Tiwari et al. (2009b) also suggested that crop intensive land use systems can have negative outcomes, including decreasing soil physical quality through repetitive tillage, and inappropriate use of fertilizers and pesticides in the mid-hills. Dahal et al. (2007) reported that increased cropping intensification altered stream water quality and chemistry—particularly with increased NH_3, NO_3 and sodium concentrations in waterways—a consequence of runoff and sedimentation in systems with increased agrochemical use with the inclusion of vegetables and potato in rotations. They also observed that more intensive agricultural practices can increase the abundance and biomass of macroinvertebrate communities, though with decreasing evenness and reduced macroinvertebrate species richness in the Ansikhola and Chakola mid-hill watersheds in central Nepal. This study also noted an increase in drinking water source contamination with fecal coliforms during the rainy season. Although not directly attributable to agricultural practices, Dahal et al. (2007) suggested that increasing densities of human settlements in locations with double cropping and vegetable farming systems, as well as heightened presence of migrant agricultural laborers, could result in water contamination. In addition to increased intensive vegetable cultivation, Brown and Shrestha (2000) suggested that dairy production should also be considered an important indicator for farming systems intensification in the mid-hills of central Nepal. Their findings suggested the crop intensification process and expanded dairy markets were associated with increased use of fertilizers and pesticides, greater demands for off-farm fodder as livestock feed (which can negatively affect the conservation of non-farm areas in cut-and-carry fodder systems), and greater use of soil and water resources, with potential for soil water and nutrient depletion.

4. Institutional and socio-economic issues and challenges in cereal-based production systems

4.1 Seed production, replacement, circulation and delivery systems

Nepal has generally two types of seed systems: formal and informal. The former is a regulated seed system with the involvement of public and private seed stakeholders, while in the informal system, there is no regulated seed production or supply system and farmers either use their own saved seeds or seeds acquired through farmer to farmer exchange. In the former, seed also enters Nepal from abroad through importing by wholesalers and large agro-dealers, who ultimately make imported seed available to farmers either directly or indirectly through sales to smaller agro-dealers (Gauchan, 2019). Regardless of the system, there is generally a low rate of varietal turn over and low seed replacement rate. It is not uncommon for farmers to make use of varieties with 36 years of age and recycle seeds for subsequent seasons. For instance, the two very common maize varieties Rampur composite and Arun-2 were released in 1975 and 1982, respectively (Joshi and Joshi, 2020).

The use of these varieties—which are still widely favored by many farmers—is still ongoing. The Nepalese seed system is nonetheless constrained by both systemic and institutional challenges. These are insufficient administration of seed production and distribution systems, and capacity development challenges, among others. In response, the Government of Nepal has developed and is in the process of implementing the 'National Seed Vision' (NSV) for the period from 2013 to 2025. Among the different milestones, the NSV aimed, inter alia, to achieve a seed replacement rate for rice and wheat of 25% and of 33% for maize by 2025, while also fostering increased private sector engagement in variety development and distribution (Gauchan, 2019; SQCC, 2013). Additional options for improvement of seed systems include agroecological zone-specific and regional marketing of varieties sold by the private sector, but produced through contract engagements with farmer cooperatives (Witcombe et al., 2010; Witcombe et al., 2005).

4.1.1 Replacement rates, seed saving, and seed production

Availability, accessibility, and affordability of quality seed is one of the major constraints of cereal-based production systems in Nepal. The seed replacement rate of Nepal's major cereals is below 20%; for paddy, maize and wheat, replacement rates are 18.4%, 15.4% and 15.2%, respectively (MoALD, 2020). A recent extensive survey in the Terai districts has shown that Nepalese farmers replace only about 17% of the seed with quality-controlled seed, of major cereals in each cropping cycle. The remaining 83% tends to be saved at home, exchanged between neighbors or relatives, or obtained from other informal sources (CSISA, 2019). In principle, this might aided in the conservation of agricultural biodiversity and the maintenance of numerous local varieties (Witcombe et al., 2005), however many of these varieties may not yield higher or have stress tolerance in comparison to more recent releases.

In Nepal, there are four generations of seed classes and two quality monitoring systems. The four classes include breeder seed, foundation seed, certified seed and improved seed. The government monitors and certifies these seed classes for their quality through a standard certification system before distribution. However, seed growers can also grow-out and supply seeds without external quality control by the government, in a system known as 'truthful labeling'. In this case, the names for second and third generation seed may be replaced as source seed and labeled seed, respectively, as opposed to the names granted for use by governmental agencies under the certification system.

Although this seed generation system is in place, subsequent seed multiplication systems in most cases do not follow it. Shortages of reliable seed (both certified or improved) at sowing is nonetheless a common problem in Nepal, due in part to the use of foundation seed for producing food grains rather than for the production of certified or source seed. The absence of a thorough seed production planning and tracking system is why the number of early generation seeds produced can be higher than later generations.

The development and transfer of new agricultural technologies, including improved stress-tolerant genotypes and hybrids, will be effective only when farmers have access to quality seeds produced and channeled through an efficient seed system (MoAD, 2013). As the national research system in Nepal is underfunded at present, challenges remain in developing seed production systems and technologies required for the country's diverse ecological settings and different typologies of farmers (Joshi and Joshi, 2020). The NSV and various studies have highlighted some of the key constraints faced by seed companies in Nepal, including (a) limited access to improved seed production technologies, (b) an unfavorable regulatory environment, and (c) restricted access to financial services to expand business operations (Gauchan, 2015, 2019; IFPRI, 2016; Mishra et al., 2017).

These issues are exemplified by current efforts to develop appropriate hybrid maize varieties. Due to a lack of well-defined policies and limited resources for hybrid maize research, Nepal has limited progress in the hybrid maize development (Gurung et al., 2011). Recognizing their high yield potential, maize hybrids were introduced more than a decade ago and grown in the Terai and Inner Terai in Nepal's eastern and central regions. Their use in the western region of Nepal and the hills has remained limited until recently. Although Nepal still produces primarily open-pollinated varieties (OPVs)—many of which are directly consumed as human food—hybrid maize grain tends to be sold to mills producing feed for the poultry industry, which is growing in Asia. As a result, maize is increasingly replacing wheat, lentil, and other winter crops in the Terai and Inner Terai, particularly in eastern and central Nepal (MoALD, 2018). In 2019, however, the amount of hybrid maize seed imported into Nepal was estimated to be sufficient for approximately 10% of Nepal's suitable maize area only, with domestic production unable to make up the difference.

This situation is at least partly due to the long variety release process for new hybrids in Nepal. The complications involved in registering and releasing varieties has resulted in expanded interest in fast track registration and the release of new varieties (Gauchan, 2015, 2019). With the recent restructuring of the government in Nepal, all nationalized banks have been directed to allocate 10% of their lending to the agricultural sector (NRB, 2018). Seed companies are yet to benefit from this decision as they frequently lack the requisite business plans required to satisfy lenders. In addition, incentives such as tax breaks or subsidies for investing in research and development, storage, or seed processing machinery are absent, a situation that contrasts with neighboring countries like India, Pakistan, and Bangladesh (IFPRI, 2016).

4.1.2 Seed storage

Availability of seed storage structures and facilities for the maintenance of quality seed is a challenge among smallholder farmers in South Asia and particularly in Nepal. Devkota et al. (2018a) reported that in Nepal, farmers often incur 15–30% losses of saved seed due to a lack of appropriate storage facilities. Farmers recycle used fertilizer bags, polythene bags, household metal containers, and mud bins, and in case of maize, hang dried maize cobs inside their homes or in temporary sheds outside homes. Cereal grains, especially maize, are particularly susceptible to aflatoxin (by-products of fungal activities of toxic strains of *Aspergillus* spp.) contamination, which starts in the soil during crop growth but can continue after harvest and during storage (Gautam et al., 2008), resulting in increasing aflatoxin levels over time (Benkerroum, 2020). In Nepal, aflatoxin contamination normally occurs in winter or spring maize in the Terai and summer maize in the hills. Fungal infections can happen when cobs have a sufficiently high moisture content, and the crop's maturation and harvesting time coincides with the early or late monsoon, respectively.

Aflatoxin producing fungi can grow exponentially under conditions of conventional grain storage, particularly as high temperature and humidity create conditions for contamination of seed or grain. Pokhrel (2016) examined 141 maize samples from five development regions of Nepal; 70% had prevalence of aflatoxin ranging from 0 to 549 $\mu g\,kg^{-1}$, with 15.7% of samples containing aflatoxin content greater than 20 $\mu g\,kg^{-1}$ (Pokhrel, 2016). Gautam et al. (2008) also reported that 42.5% of maize samples collected in Kathmandu valley were contaminated with aflatoxin AFB1, and that they had average content of 50.2 $\mu g\,kg^{-1}$. These studies suggest that maize seed or grain produced for food and feed in Nepal is likely to contain high to toxic levels of aflatoxin, which could complicate human and animal health. For example, the consumption of food containing aflatoxin concentrations of 1 $mg\,kg^{-1}$ or higher can cause aflatoxicosis. Based on evidence from previous outbreaks, estimates are that when aflatoxin is consumed for over 1–3 weeks, a dose of 20–120 $\mu g\,kg$ body weight^{-1} day^{-1} is enough to be accurately toxic. Such a dose may also be potentially lethal. As such, maximum permitted levels of aflatoxins tend to be in the range of 0.5 to 15 $\mu g\,kg^{-1}$ (WHO, 2018).

Obtaining acceptable levels of seed germination after storage can also be a challenge. Harris et al. (2001), reported that wheat seed priming by soaking seed with water overnight or by 0.2% gypsum solution increased germination and improved establishment, increased wheat yield, and reduced production cost. Pandey and Koirala (2017) suggested that following storage, maize seed priming increased germination percentage and grain yield when compared to non-primed seeds in Nepal's hill districts. Due to high rainfall rates (greater than 1200 mm year^{-1}) and with greater than 80% of the rainfall occurring during the summer monsoon season from June–September, however, seed-priming may not be overly useful in lowland transplanted rice. It may nonetheless be worthwhile for upland or direct-seeded rice in more water-limited environments (Farooq et al., 2006), as well as for other winter season crops including lentil, chickpea, maize, among others (Harris et al., 2001).

4.2 The feminization of agriculture

Agricultural feminization—which can be defined as the quantifiable increase of women in agricultural decision making and farm management—can happen in several ways. In South Asia, this process has tended to occur where men who otherwise would make most farm management decisions take up non-agricultural jobs within and beyond their residence, and women take charge of agricultural activities. The process of feminization has two dimensions: women's participation in agriculture as unremunerated family laborers or wage workers (labor feminization) or as independent producers (managerial feminization). The nature and extent of feminization revolve around these two overlapping processes (Lastarria-Cornhiel, 2008). While feminization processes are traditionally viewed as a result of industrialization, recent changes in South Asia indicate that this is not always the case. In Nepal, for example, the main factors for this phenomenon include male out-migration from rural areas (Adhikari and Hobley, 2015; Gartaula et al., 2010), and also Maoist insurgency (Upreti et al., 2016). During the insurgency between 1996 and 2006, many rural male youths joined the militia on a voluntary or involuntary basis. More recently, an increasing number of Nepali youths are leaving the country to join the international job markets especially in the middle eastern countries, Malaysia, and South Korea. Data show that approximately 70% of labor migrants are youth; 87% of them are male. In terms of regional patterns, the rate of male youth out-migration is about the same from Nepal's hills (36%) and the Terai (35%) (Bossavie and Denisova, 2018). Consequently, many farm management decisions have been left in the hands of rural women, remaining youth, and the elderly. This process of change has important social, cultural, economic, and policy implications for longer-term agricultural development.

Women remaining on farms use different strategies to address resulting labor shortages. In some cases, agricultural land is underutilized or fallowed (Jaquet et al., 2019; KC and Race, 2019). Land fallowing is more frequently found in the hills (Jaquet et al., 2019; KC and Race, 2019), while strategies to tackle labor shortages in the Terai include arresting the conversion of agricultural and into other uses (Gartaula et al., 2012). This can result in declining agricultural productivity in the long run on one hand (Massey et al., 2020), or increased agricultural mechanization to cope with labor shortages on the other (Paudel et al., 2020b). Another major consequence of agricultural feminization is women assuming control over non-traditional activities that were otherwise within the domain of men's management (Adhikari and Hobley, 2015; Gartaula et al., 2010). These changes involve shifts towards labor feminization and managerial feminization, the former with more women entering into the hired agricultural labor force to generate income. The latter—in which women take on leadership roles in agricultural decision making—can also lead to women's empowerment. Holmelin (2019), for example, documented that where women are known within their communities as active farm managers, that their social capital and prestige may increase. This was more so among women-headed households than male-headed households where in-laws and non-resident husbands assumed the role of the primary farm manager and decision-maker after husbands migrated

(Gartaula et al., 2017; Spangler and Christie, 2020). Despite these changes, many women with family members who have migrated face challenges, including increased workloads and economic insecurity (when remittances are sporadic). Some may also lack the capacity to use or reallocate household and farm resources due to their limited access to and control over the productive resources—even in the absence of the primary male head of the household.

4.3 Farm mechanization

Farm power in Nepal is overarchingly reliant on animals (41%), followed by human power (36%). Machinery is still far less widely used—particularly outside of the Terai—with less than a quarter of all farm power coming from engine-based sources (Shrestha, 2013). Farm mechanization in Nepal started in the early 1970s by introducing four-wheeled tractors, followed by two-wheeled tractors (also known as power tillers in South Asia). Rotavators, combine-harvesters, and threshers soon followed in the Terai and Inner Terai districts (Biggs et al., 2011; Gauchan and Shrestha, 2017; Justice and Biggs, 2013). Inclusion of non-animal or human farm power sources in Nepal's hills is challenging due to rugged topography, the heavy weight of machines, and the need to transport them up and down terraces and between fragmented farm plots and villages (Paudel et al., 2019b; Tiwari et al., 2004). Takeshima (2017, 2019) reported that less than 8% of the farms in the hills and mountains regularly used mechanical tillage, compared to more than 46% in Terai and Inner Terai. In the mid-hills, mechanization in earnest started only after 2010, when mini tillers (5–7 HP) used for land preparation were imported from China (Biggs et al., 2011; Justice and Biggs, 2013). Since this time, mini-tillers have become far more widespread (Paudel et al., 2019b; Paudel et al., 2019c; Paudel et al., 2020a,b,c). Paudel et al. (2019b) also reported that increasing rural labor wage rates and the declining availability of draft animals were the major drivers of mini tillers adoption in the mid-hills of the mid-western region. In the Terai, Nepal, and Thapa (2009) analyzed factors determining agricultural mechanization in a peri-urban center in eastern Nepal; their conclusion was that the degree of market-oriented agricultural activities was affected by the availability of machinery to farmers.

The importance of scale-appropriate farm mechanization (e.g., use of mechanized farming implements appropriate to the limited land sizes and resource endowments of smallholder farmers (cf. Krupnik et al., 2013)—for agricultural development was only realized more fully when the

Government of Nepal developed a farm mechanization policy and the subsequent Agricultural Development Strategy for 2015–2035, with the provision of subsidies for select farm machines (ADS, 2015; Gauchan and Shrestha, 2017; Paudel et al., 2019b). These developments stimulated the commercial availability of farm machines such as mini-tillers, rotavators, multi-crop planters, power tiller operated seeders, zero-till drills, and rice transplanters, in addition to multi-crop reapers and combine-harvesters and threshers. Rice and maize grain dryers also began to appear in the Terai and mid-hill regions, though more prominently in the former than the latter (Acharya, 2017; CSISA, 2019; Paudel et al., 2019b). Alongside these developments, farmers' access to machinery began to expand through service provision arrangements—in which machinery owners offer rental or use of machinery services to farmers on what is generally an affordable fee-for-service arrangement—mirroring processes observed in India and in Bangladesh (CSISA, 2019; Keil et al., 2016; Paudel et al., 2019b; Van Loon et al., 2020).

The major reasons for increased use of mechanization equipment in Nepal appear to include favorable government policy (implementation of subsidy scheme), strengthening of the import and supply value chain by enabling the growth of the private sector, and supportive on-farm research and training efforts implemented through research centers and development agencies (CSISA, 2019, 2020; Takeshima, 2019). A recent census-scale survey of 31,110 households in Nepal indicated that mechanized combine harvesting was used by 19% of farmers, followed by 12% using mini-tillers (CSISA, 2020). Although dramatic growth in two-wheel tractor attachable and self-propelled reapers has been dramatic over the last 5 years in Nepal, still only 3% of households appear to access their use. An equal number of households make use of laser land levelers or maize threshers, while under 1% use mechanical maize seeders or rice transplanters.

4.4 Agricultural insurance and climate risk management

An increasingly popular strategy to mitigate the effects of climate change and extreme weather events is through both indemnity and weather index insurance for crops and livestock (Fisher et al., 2019; Greatrex et al., 2015). Since 2014, the Government of Nepal has engaged rural communities by offering a 75% subsidy on insurance premiums (Ghimire et al., 2016a). Several insurance companies now have mandates to cover different districts and improve farmers' access to insurance. However, a mediocre level of awareness on the importance of agricultural insurance among farmers has hindered the wide-spread uptake in Nepal, despite the presence of heavy subsidy (Ghimire et al., 2016a). Budhathoki et al. (2019) studied farmers' willingness to pay for index (area-yield) based insurance in the Terrai. They identified that farmers were willing to pay USD 42 and 30 ha^{-1}, respectively, for rice and wheat insurance. These rates were more than three times the value of the subsidy premium on offer in Nepal, indicating that the low rate of insurance uptake is unlikely to be related to the costs of enrollment, but rather due to a poor understanding of many farmers of the relationship between climate variability and crop productivity risks, as well as the fundamentals of how insurance works. In addition, improvement of current claim settlement procedures including awareness raising through farmers' institutions were identified as additional ways to enhance adoption of agricultural insurance schemes in Nepal (Ghimire et al., 2016b). Other governmentally sponsored agricultural development programs such as youth self-employment schemes, spring rice promotion, and other grant and subsidy programs have begun to link agriculture insurance to their interventions. More recently, provision of insurance has been made mandatory in order for farmers to receive any agricultural subsidy support from the government. However, Timsina et al. (2018a) reported that this strategy has not adequately addressed the problem of low agricultural insurance enrolment, indicative of the need to further revise insurance schemes, as advised by Budhathoki et al. (2019).

4.5 Water resources management

With 210 million m^3 of annual renewal water resources, Nepal is one of the richest countries in the world in terms of water endowment (FAOSTAT, 2019). But more than 70% of the precipitation and associated river discharge in Nepal occurs during the monsoon months from June to September, rendering the productive use of these water resources a major challenge as storage opportunities are limited (Biemans et al., 2016; Nepal et al., 2019). Over the last decades, both farmer and government managed irrigation schemes have been studied and multiple guidelines for improving their management have been proposed, but large sediments loads, regular destruction of headworks, and institutional inefficiencies hamper their expansion, management, and the validity of their underlying business model in an increasingly privatized and cash-based rural economy (Lam, 1996; Ostrom and Gardner, 1993; Renault et al., 2007). Especially in the Terai, increased private investment in small scale groundwater irrigation systems by farmers and government agencies accelerated since the early 2000s. This trend follows the 'groundwater boom' observed in India and elsewhere in South Asia (Shah et al., 2006; Urfels et al., 2020, 2021). An estimated 600 mm average annual groundwater recharge generally sidelines concerns about depletion, although aquifer reserves and precipitation patterns vary markedly across districts (Shrestha et al., 2018). Groundwater irrigation thus fills part of the gap where surface schemes do not provide reliable water services, a function that Nepal's most recent Irrigation Master Plan indicates as the most viable investment option for future irrigation development in Nepal (DWRI, 2019).

Yet despite more than two decades of initiatives and policies favoring groundwater development, neither have the demands for access to reliable irrigation been saturated nor have the benefits of existing infrastructure distributed equally. Similarly, groundwater use and aquifer reserves are largely unmonitored (Sugden, 2014; Urfels et al., 2020, 2021). *Re*-evaluating current conceptions about pump selection that favor oversized pumps, and with efforts to encourage the use of smaller, more efficient, and more affordable pumps, new water development initiatives may increase efficient pump ownership and hence water use and land productivity (Foster et al., 2019; Urfels et al., 2020, 2021). In addition, heavy subsidy programs favoring solar powered irrigation systems have, due to the attractiveness of renewable energy promotion, stimulated a large roll-out with more than 1600 installations of solar irrigation pumps to date, aiming to cover at least 22,000 ha by 2030 (MoEWRI, 2018; Mukherji et al., 2017). But their long-term and in-field viability, especially for cereal farming at non-subsidized rates, remains questionable (Shah et al., 2018). No matter the energy source, a well-capacitated and supporting private sector (e.g., for well drilling, pump selection/system design, spares and repairs) and well-informed approach to irrigation scheduling both present technology independent entry points to strengthen pro-poor, reliable, cost-effective, and sustainable groundwater use (Justice and Biggs, 2020).

A simple and locally effective monitoring system is required to ensure that groundwater use does not exceed local annual recharge potential, or is limited by a lack of institutional capacity (Suhardiman et al., 2020). Bonsor et al. (2017) and Shrestha et al. (2018) have characterized the Terai's aquifer systems. Specifically, they highlight the complex layering of aquifers, river system (megafan) dependent spatial heterogeneity, and contributions of the Bharbar zone, at the foothills of the Himalayas, to groundwater recharge. In the same vein, more granular understanding of local aquifer characteristics may not only contribute to an understanding of the potential function of the aquifer system for irrigation water supply, but also to storage provisioning for flood prevention (Bharati et al., 2016; Khan et al., 2014; Muthuwatta et al., 2017). Better knowledge (and management thereof) of the subsurface can also guide the design of drainage systems that are needed to address waterlogging constraints which hamper land productivity in a significant share of poorly drained areas, especially in good rainfall years (Paudel et al., 2020a,b,c; Ritzema et al., 2008).

4.6 Extension systems

A functional innovation and extension system is integral to resolving many of the constraints and opportunities discussed throughout this paper, yet while Nepal has undertaken governmental restructuring and a decentralization of authority to local government in line with its 2015 constitution, challenges remain in delivering agricultural mandates. As with health and education, agriculture falls concurrently to the responsibility of all three levels of government—federal, provincial, and local—under the new constitution. The federal level is charged with scientific research, technological and human resource development, while the provincial and local levels are responsible for management, and the operation and control of agricultural extension services. This decoupling of research and innovation from extension without sufficient functional linkages could perpetuate a top down and unresponsive rural extension system without a mandate or clear process for linking research, extension and development in an iterative learning processes. For example, NARC, extension services under the Department of Agriculture (DoA), and national universities function largely independently. Although this permits some level of autonomy, it also limits integration and collaboration, at times resulting in strained relationships.

Under the previous constitution, the DoA and Department of Livestock (DoL) were responsible for provision of extension through district-level agricultural officers. However, as Nepal's district system was disbanded under the new constitution in favor of provincial and local governments, these newly formed bodies have been tasked with the implementation of extension services despite limited capacity and funding. For example, at the provincial level, the Ministry of Land Management, Agriculture and Cooperatives provide oversight, though the Federal government provides funding and staffing control that can limit the functional autonomy and abilities of local governments to administer extension services (Babu and Sah, 2019; Kyle and Resnick, 2019). Yilmaz et al. (2020) also highlighted the complications of the rapid shift in responsibility to local government, which has absorbed new responsibilities—often without considerable experience—not previously assigned. In terms of ability to monitor outcomes and performance in agricultural development, only 11% of Nepal's local level governments were reported to have adequate personnel. Only 7% had adequate resources, 19% had adequate knowledge, and 5% had adequate physical infrastructure. Transitioning to private or farmer-cooperative oriented extension systems is also unlikely due to the limited technical and financial capacity of both the private sector and of local cooperatives. The latter is usually constrained to the provision of credit services to farmers only, due to limited technical and managerial knowledge (Thapa, 2010). Babu and Sah (2019) and Kyle and Resnick (2019) summarize that the institutional capacity in terms of human resources, infrastructure, funds and other resources, is currently insufficient to enable functionality.

5. Agronomic research findings in cereal-based production systems

5.1 Yield trends

Developing an understanding of yield trends in farmers' fields and comparing farmers' yields with climatically limited potential yield can assist in identifying crop yield gaps and strategies to overcome them. In Nepal, the amount of land area of maize, wheat and millet more than doubled during 1977–2017, although rice area increased by only 23%. The average yield of wheat increased by more than 100% (1.04 to 2.55 $t\,ha^{-1}$) during this period, but rice yield by only 87% (1.8 to 3.37 $t\,ha^{-1}$). A gain of 54% in maize yield (1.66–2.55 $t\,ha^{-1}$) was also observed (FAOSTAT, 2019), with hybrids contributing to some of this increase (Devkota et al., 2016). There was not much yield gain during this period for millet (1.0 to 1.16 $t\,ha^{-1}$) (FAOSTAT, 2019), presumably due to insufficient research and development emphasis on minor cereals. Approximately 70% of rice area in the country is either partially or fully irrigated. Likewise, 66% of all wheat area is partially or fully irrigated, with 81%, 46% and 46% of the areas respectively in the Terai, hills, and mountains (MoALD, 2018; Table 6). In contrast to data reported by FAOSTAT (2019), information collected from farm households indicate declines in rice and wheat yields in all agroecological zones, although yield trends for maize were reported to have increased in the Terai due to increased use of hybrids. Maize yield remained stable in hills and mountains (CBS, 2019; Fig. 14), a partial reflection of the predominant use of OPVs and limited access

Table 6 Comparison of crop areas and yields across three agroecological regions of Nepal in 2019.

Parameter	Crop5	Agroecological region			Total
		Terai	Hills	Mountains	
Crop area (Million ha)	Rice	1.10	0.40	0.06	1.6
	Wheat	0.42	0.26	0.05	0.7
	Maize	0.15	0.66	0.09	0.9
	Millet	0.01	0.21	0.05	0.3
Crop yield ($t\,ha^{-1}$)	Rice	3.49	3.17	2.47	3.37
	Wheat	2.94	2.18	1.40	2.55
	Maize	2.87	2.53	2.23	2.55
	Millet	1.07	1.17	1.14	1.16
Area irrigated (%)	Rice	75.00	60.00	51.00	70.00
	Wheat	81.00	46.00	46.00	66.00
Irrigated yield ($t\,ha^{-1}$)	Rice	3.86	3.44	2.85	3.74
	Wheat	2.96	2.20	2.00	2.72
Rainfed yield ($t\,ha^{-1}$)	Rice	2.37	2.78	2.06	2.49
	Wheat	1.24	1.87	0.89	1.75

From FAOSTAT, 2019. United Nations Food and Agricultural Organisation. http://www.fao.org/faostat/en/#data; MoALD, 2019. Statistical Information on Nepalese Agriculture 2017-2018. MoALD, Kathmandu, Nepal.

to inputs (Devkota et al., 2016). Farmers' use of improved varieties of rice, wheat and maize are more common, and are estimated to be in excess of 90% (MoALD, 2018), with greater use in the Terai and Inner Terai than hills or mountains. In maize, improved OPVs are used in mid- and high-hills, but both OPVs and hybrids are found in the Terai and Inner Terai (MoALD, 2018). Analysis of long-term yield and area expansion data shows the millet yield has been nearly stagnant from 1961, with yield increase of only $1.3\,kg\,ha^{-1}\,year^{-1}$ (FAOSTAT, 2019).

There are substantial differences in average yields of these cereals among the three agroecological zones, which are heavily influenced by water availability and irrigation regimes (MoALD, 2018). Average yields of rice, maize, wheat and millet, respectively ranged from 2.47, 2.23, 1.40 and $1.14\,t\,ha^{-1}$ in the mountains, to 3.49, 2.87, 2.94 and $1.07\,t\,ha^{-1}$, respectively, in Terai in 2018, with intermediate yield levels in mid-hills. Higher wheat yields in the hills compared to the Terai were due to cooler temperatures and longer growing season. Average yields of rice and wheat are substantially greater under irrigation (3.74 and $2.72\,t\,ha^{-1}$, respectively) than under rainfed conditions (2.49 and $1.75\,t\,ha^{-1}$, respectively) (MoALD, 2018). Yields of the improved OPVs of maize tend to range from 2.31 in the mountains to

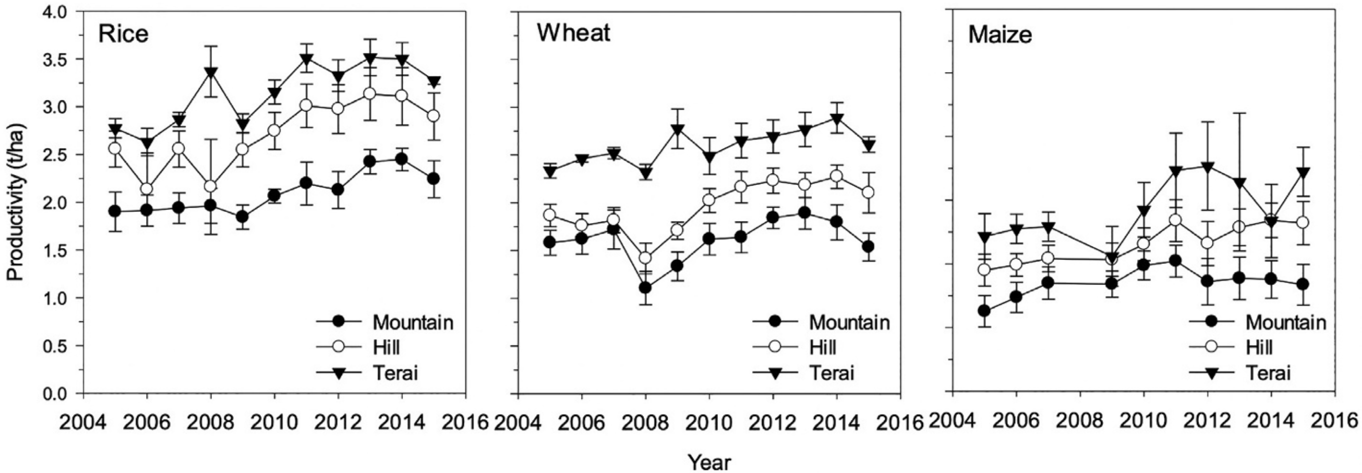

Fig. 14 Yield trends of rice, wheat and maize in mountain, hill and terai region of Nepal. Vertical lines are standard error across five (eastern, central, western, mid-western, and far-western) regions from 2005 to 2015. *Data from CBS, 2019. Statistical Year Book of Nepal-2019. Government of Nepal, National Planning Commission Secretariat, Central Bureau of Statistics, Ramshahpath, Thapathali, Kathmandu. https://unstats.un.org/unsd/environment/Compendia/Nepal_Environment%20Statistics%20of%20Nepal_2019.pdf.*

2.87 $t\,ha^{-1}$ in the Terai, while that of local varieties ranges from 1.26 in the hills to 1.40 $t\,ha^{-1}$ in the mountains (CBS, 2019; MoALD, 2018). Both OPVs and local varieties require fewer external inputs (particularly fertilizers) than hybrids and produce moderate but stable yield levels. OPVs are also less expensive and more affordable for resource-poor farmers, especially in the mid- and high hills (Thapa et al., 2019). A study on the adoption of OPVs showed that 83.3% of farmers saved their own seeds or obtained seed from fellow farmers, whereas only 16.7% obtained OPVs from governmental organizations. More recently, however, the Government of Nepal has adopted agricultural development policies aimed at the development of both locally-adapted hybrids and OPVs, with measures to increase availability of maize seeds to resource-poor farmers (Gauchan, 2019; Thapa et al., 2019). For example, goals include the release 423 new open pollinated and 60 new hybrid varieties by 2025 (MoAD, 2013). Yields of maize hybrids in experiment stations as well as farmers' fields under relatively non-limited input conditions in the Terai were reported be as high as 12 $t\,ha^{-1}$ (Pandey and Koirala, 2017).

5.2 Yield potential and yield gaps

The yield potential (Yp) of a crop cultivar c defined as yield of the cultivar grown without water and nutrient limitations, and free of biotic stresses (Penning de Vries et al., 1989). As such, irrigated farming systems with carefully implemented and appropriate agronomic practices are more likely to reach Yp. In rainfed systems, abiotic stresses also need to be non-limiting to achieve Yp, although water-limited yield potential (Yw) is determined by soil water availability for crop growth, which in turn depend on soil and terrain properties. The yield gap (Yg) may be defined as the difference between Yp and Yw, or between Yp and the actual yield obtained by farmers (Penning de Vries et al., 1989; Timsina et al., 2018b).

An earlier study in the central Terai of Nepal revealed large gaps between Yp and those typically obtained on research stations (Yg 1), between research stations and yields obtained by farmers (Yg 2), and also between Yp and yields obtained by farmers (Yg 3). A larger Yg 3 was found than Yg 1 or Yg 2 for cereals, pulses, tubers, and oilseeds (Amgain and Timsina, 2004) (Table 7). For rice, Yg 1 was larger than that for maize grown with OPVs, and also for wheat, suggesting that use of high-yielding varieties and improved crop and soil management practices are likely to be required to reduce this gap. Yg 2 was larger for wheat than for the other two crops, suggesting that farmers' current

Table 7 Yields and yield gaps ($t\,ha^{-1}$) of major crops in Chitwan, located in the central region of Nepal.

Crop	Potential yields (A)	Research station yields (B)	Farmers' yields (C)	Yield gap 1 (A-B)	Yield gap 2 (B–C)	Yield gap 3 (A–C)
Cereals						
Rice	8.10	3.40	2.74	4.10	0.66	5.36
Maize	6.30	3.30	1.82	3.0	1.48	4.48
Wheat	5.03	3.50	1.88	1.53	1.62	3.15
Oilseeds						
Rapeseed or mustard	1.10	1.00	0.71	0.10	0.29	0.39
Legumes						
Soybean	2.00	1.50	0.85	0.50	0.65	1.15
Lentil	2.50	1.75	0.82	0.75	0.93	1.68
Tubers						
Potato	20.0	16.5	10.9	3.50	5.60	9.10

Adapted based on data from Amgain, L.P., Timsina, J., 2004. Crop and cropping systems research in the central Terai, Nepal. In: Fischer, R. A. (Ed.), Proceedings of the 4th International Crop Science Congress, 'New directions for a diverse planet', September 26—October 1, 2004, Brisbane, Australia. https://www.academia.edu/10221486.

management for wheat has limitations. In addition, Amgain and Timsina (2004) also discussed the importance of non-agronomic factors, for example access to appropriate extension services, which can assist farmers to reduce yield gaps. The larger Yg 3 for soybean, lentil, and potato suggests considerable scope for yield increases in farmers' fields through improved varieties and management, while a smaller gap for rapeseed and mustard suggests less scope for improvement.

Exempting wheat, these data reveal that the Yp of all crops, except wheat, were smaller in Nepal than what is normally expected for sub-tropical regions of Asia (FAOSTAT, 2019). For example, Timsina et al. (1997) reported that the long-term mean Yp of rice (greater than $8\,t\,ha^{-1}$) and maize OPV (greater than $6\,t\,ha^{-1}$) estimated by the DSSAT-CERES models were much larger, while that of wheat was lower (at about $4.2\,t\,ha^{-1}$) than recent estimates for various locations in Nepal (Devkota et al., 2015, 2016, 2018b). Timsina et al. (1997) and Amgain and Timsina (2004) both concluded that cereal yields in farmers' fields may be decreased by unbalanced use of synthetic fertilizers, poor soil fertility management, and negative nutrient balances. Sub-optimal use of irrigation, damage by insects and diseases, and recurrent flooding during the monsoon are additional constraints. Recent studies using Nutrient Expert (NE) for Maize, a decision support tool developed based on the principles of site-specific nutrient management (SSNM), have shown that maize yields in the Terai and western mid-hills regions can be increased and gaps decreased by reducing the discrepancy between yields estimated by NE and either farmer' practice or extension recommended fertilizer rates by using SSNM recommendations (Bhatta et al., 2020; Devkota et al., 2015, 2016, 2018b). Application of fertilizers considering indigenous soil nutrients reservoirs and farmers' application of organic manures on a site-specific basis resulting from NE recommendations resulted in higher maize yields and reduced Yg compared to farmers' common practices of relying only on organic sources of nutrients with no or minimal application of inorganic fertilizers. They also compared favorably to extension blanket recommendations for inorganic fertilizers.

In the past two decades, the Yp of the three major cereals in Nepal has increased due to the use of maize hybrids and improved varieties wheat, particularly those that are tolerant to abiotic constraints. Using the ORYZA 2000, Hybrid Maize and CERES Wheat models, Timsina et al. (2010, 2011) estimated climatic Yp as high as 12 t ha^{-1}, 15 t ha^{-1} and 6 t ha^{-1} for rice, maize and wheat, respectively, in Chitwan in the central Terai. These results were obtained when optimum planting dates and long-duration varieties were modeled for growth under non-limiting conditions of water and nutrients, with and pest and diseases fully controlled. In intensive cropping systems where two or more than two crops per year are grown, short- or medium-duration varieties (which have slightly reduced Yp) are necessary to permit sufficient time for growth of each crop within their respective cropping seasons. This results in higher 'systems' yield of both crops combined than each of the individual crops with longer growth durations if grown separately (Timsina et al., 2010, 2011), and as compared to earlier studies by Timsina et al. (1997) and Amgain and Timsina (2004). Recently, Devkota (2017) simulated the Yp of Radha-4, Sabitri and Swarna, three commonly used rice varieties, across eight Terai districts. Devkota et al. (2016) also simulated the attainable yield of Manakamana-3, a maize OPV, across nine mid-hill districts. The mean Yp of the rice varieties ranged from 7.5 to 8.8 t ha^{-1}, while that of maize ranged from 5.0 to 7.5 t ha^{-1} (Fig. 15). The lower rice yields compared to earlier estimates by Timsina et al. (2010, 2011) were due to differences in climate and varietal characteristics. The difference in maize was due to the use of an OPV rather than hybrid variety.

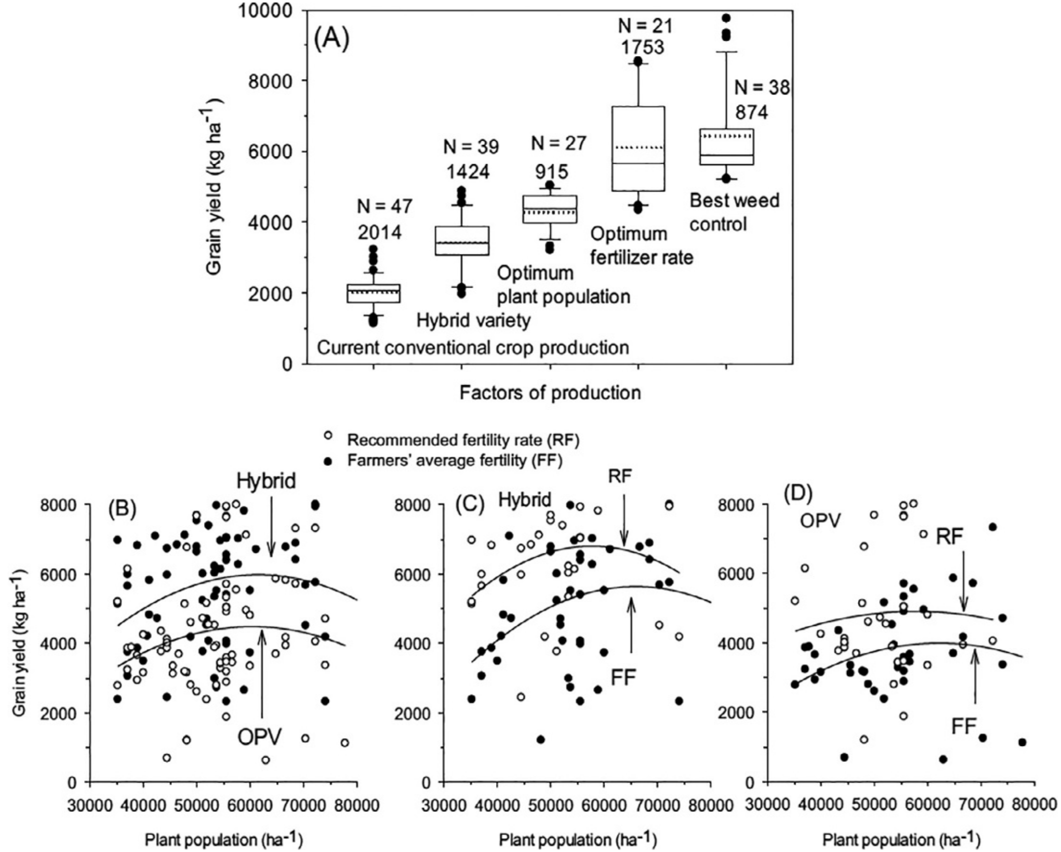

Fig. 15 Contribution of different factors of production for closing the maize yield gap (A), and grain yield as a function of variety, plant population and fertilizer rate (B, C, and D) in Palpa, a mid-hill district of Nepal. *n* indicates the number of on-farm experiments conducted. *Data from Devkota, K.P., McDonald, A.J.J., Khadka, L., Khadka, A., Paudel, G., Devkota, M., 2016. Fertilizers, hybrids, and the sustainable intensification of maize systems in the rainfed mid-hills of Nepal. Eur. J. Agron. 80, 154–167. https://doi.org/10.1016/j.eja.2016.08.003; CIMMYT-IFAD, 2013. Sustainable Intensification of Smallholder Maize-Livestock Farming Systems in Hill Areas of South Asia, CIMMYT, Kathmandu, Nepal. https://www.kullabs.com/classes/subjects/units/lessons/notes/videoplay/272/153.*

Although simulation models can be useful to estimate crop Yp and Yg, estimates based on farmer surveys or crop cut data are also useful evidence for identifying what farmers can achieve in their own fields. Pandey and Koirala (2017) reported that mean maize yield of OPVs from the best management treatment on experiment stations was 6.7 t ha^{-1}, while yield from researcher-managed trials in farmers' fields was 5.7 t ha^{-1}. These contrast with the national average yield of 2.5 t ha^{-1}, indicative of a large Yg in maize, underscoring the considerable potential for yield improvement. Based on recent wheat crop cut data with over 5000 observations of famers' crop management practices across several Terai districts from four provinces in Nepal, CSISA (2019) reported that the use of improved agronomic practices has the potential to enhance wheat yield if the 80% of farmers observed employ similar management practices to those being used by the top 10%. Subsequent machine learning analysis identified that earlier sowing to avoid terminal heat stress, increased N application and weed management as the most important drivers affecting wheat yield. In particular, surveys indicated that current application levels of N and K (88 and 11 kg ha^{-1} respectively) were below the rates for optimum response (150 and 50 kg ha^{-1} N and K_2O respectively). Data from similar crop cut surveys in rice indicated only 3.5 kg ha^{-1} K_2O application and that higher rice yields could be obtained with 110 kg ha^{-1} of N, 70 kg ha^{-1} P_2O5, and 40 kg ha^{-1} K_2O in the western Terai region (CSISA, 2019).

Devkota et al. (2018b) also reported that the Yg of wheat and mustard, estimated as difference between yield obtained with the highest-yielding versus farmer's average practices, were higher in western mid-hills than in the central Terai. They also found that the yields of both crops could be increased and yield gaps reduced by application of more balanced nutrients and use of precise crop management practices. These findings are consistent with Panaullah et al. (2006) and Timsina et al. (2010,2013), highlighting the need to improve N and K management practices to increase rice, maize and wheat yields and close Yg in rice-wheat and rice-maize rotations in Nepal's Terai region. Devkota et al. (2016) and CIMMYT-IFAD (2013) also decomposed each factor of production and examined how management practices contribute to yield gaps, e.g., contribution from variety, fertilizer, and plant population, in rainfed and OPV maize in a hill district of Palpa (Fig. 16). They also showed yield ranged as a function of variety, fertilizer rate and plant population, and can be increased from 2 to >6 t ha^{-1}.

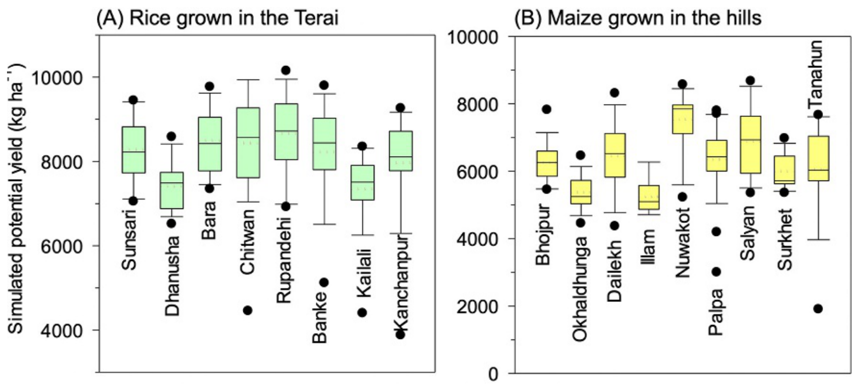

Fig. 16 (A) Simulated climatic potential grain yield (kg ha^{-1}) of rice with released varieties (Radha-4, Sabitri and Swarna) across eight Terai districts. (B) Attainable yield (kg ha^{-1}) of the open pollinated, Manakanana-3 maize variety with high rates of fertilizer (180:60:60 kg N:P_2O_5:K_2O ha^{-1}) in different mid-hill districts. Dotted lines within the box plot represent mean and the solid lines are the median. *Devkota, K.P., McDonald, A.J.J., Khadka, L., Khadka, A., Paudel, G., Devkota, M., 2016. Fertilizers, hybrids, and the sustainable intensification of maize systems in the rainfed mid-hills of Nepal. Eur. J. Agron. 80, 154–167. https://doi.org/10.1016/j.eja.2016.08.003.*

5.3 Alternative crop and soil management practices

This review recognizes the role of indigenous knowledge in the ways in which farmers manage their agroecosystems, particularly in the hills and mountains of Nepal, where access to extension services is limited and markets for agricultural inputs are few and far in-between. On the other hand, the review has also identified unsustainable land and crop management practices in these environments that can contribute to soil, water and nutrient losses through soil erosion, in addition to challenges pertaining to water quality contamination. Systematic research to develop appropriate crop and soil management practices to overcome these challenges and increase productivity, efficiency, and environmental outcomes—including the maintenance of soil fertility—remains an important need.

Conservation agriculture (CA)—which consists of practices that reduce or eliminate tillage, retain living or dead mulches on the soil surface, and diverse crop rotations—has been advocated globally to increase crop productivity, reduce labor use and farm inputs, and increase resource-use efficiencies and farmers' income, especially in the low-lying including Indo-Gangetic Plains that encompasses the Terai (Jat et al., 2014; Kassam et al., 2019). CA has also been advocated to increase energy- and labor-use efficiency while reducing greenhouse gas emissions (Gathala et al., 2020; Laborde and McDonald, 2019). In the Indo-Gangetic Plains of South Asia, a large body of literature exists on the positive effects of CA and zero-tillage compared to conventional practices (Dixon et al., 2019, 2020; Islam et al., 2019; Keil et al., 2017). Yet despite these efforts, farmers' adoption has been slow (Keil et al., 2017; Singh et al., 2012).

In Nepal, research on CA and resource-conserving technologies (RCTs, i.e., reduced tillage, residue retention, direct-seeded rice, mechanical transplanting of rice, laser land leveling, etc.), particularly in rice-wheat systems, was started in early 1980s, together with other South Asian countries, under the umbrella of the Rice-Wheat Consortium (Harrington and Hobbs, 2009). Much of this work has been continued through the CSISA and Sustainable and Resilient Farming Systems Intensification in the Eastern Gangetic Plains projects, in addition to related initiatives (Dixon et al., 2019, 2020). However, there are few published studies comparing CA with conventional management in the hills and mountains of South Asia, nor in the mid- and high-hills of Nepal (Karki et al., 2014a,b). This section accordingly presents a review of crop and soil management practices in the mid-hills and Terai regions, aiming to identify how CA and similar RCTs, together with integrated soil fertility and agroecological pest management practices, could form the basis of improved agronomic practices addressing soil and nutrient losses, as well as low crop productivity in the hills and Terai.

5.3.1 Soil, tillage, and water management

Annual soil erosion rates and resulting nutrient losses from terraced lands with intensive tillage in hills and mountains vary considerably; reduced tillage (RT) could be a potential option to reduce such losses where farmers are unable to adequately terrace their land. Brown and Shrestha (2000) and Partap and Watson (1994) reported losses of SOM, N, P, and K up to 150–600, 7.5–30, 5–25 and 10–40 kg ha^{-1} yr^{-1}, respectively, from terraced but poorly maintained lands with conventional tillage (CT). Schreier et al. (2001) reported soil loss from sole maize grown using RT, while Partap and Watson (1994) and Schreier et al. (1998) reported losses up to 5–35 t ha^{-1} yr^{-1} from CT. Tiwari et al. (2009c) suggested that RT with residue retention in maize-cowpea rotations was more effective in maintaining soil fertility and increasing farm income compared to a maize-millet rotation. Atreya et al. (2005) reported no differences in maize yield between different tillage treatments, but total annual soil and nutrient losses in RT (11.1 t ha^{-1}, 126 kg SOC ha^{-1}, 11.8 kg N ha^{-1}, less than 1 kg P ha^{-1} and 2.4 kg K ha^{-1}) were lower compared to CT (16.6 t ha^{-1}, 188 kg SOC ha^{-1}, 18.8 kg N ha^{-1}, less than 1 kg P ha^{-1} and 3.8 kg K ha^{-1}) in a central mid-hill location in the Kathmandu valley. Atreya et al. (2008) found significantly lower annual and pre-monsoon soil and nutrient losses with RT and rice straw mulching compared to CT, but neither conservation approaches neither significantly reduced runoff nor increased maize yield compared to CT. These studies suggest that RT could be a viable option for minimizing soil and nutrient losses without sacrificing crop yields in the mid-hills of Nepal, although efforts are needed to overcome perceptual hurdles to adoption among farmers.

Tiwari et al. (2008b) reported that RT decreased runoff by 7–11% and soil loss by 18–28% compared to CT in a mid-hill watershed in the central region of Nepal. Tiwari et al. (2009b) demonstrated that there are higher amounts of SOC, total N, available P and exchangeable K losses from intensively tilled commercial vegetable plots due to higher amounts of sediment displaced by erosion, with higher nutrient concentrations than from the RT plots. Although focused on vegetables, similar findings are likely to apply in cereals; RT had higher soil surface roughness due to the small ridges formed by intercultural operations and higher ground cover due to retention of crop residue, resulting in reduced soil particle detachment, reduced runoff, and increased infiltration. In contrast, commercial vegetable production and farmers' practice plots had greater soil disturbance due to intensive tillage, and smaller amounts of residues retained on the soil surface, resulting in increased runoff and decreased infiltration (Table 8). These findings suggest that RT alone would not effectively reduce runoff and soil loss in the upland terraces. Rather, a combination of RT with a living or dead mulch would likely be required to mitigate early rainstorm impact.

McDonald et al. (2006a,b) compared the effect of six rice tillage and crop establishment practices on soil physical properties and wheat following rice over two cycles in a rotation on a silt loam soil in the central mid-hills at Khumaltar in the Kathmandu valley. During the rice season, there was no effect on saturated hydraulic conductivity (Ksat) and bulk density (BD), though Ksat was higher in plots under direct-seeded rice (DSR) than transplanted rice. BD, measured after harvest of each crop, was also higher after transplanted rice than DSR. In wheat, there was no effect on BD, soil moisture retention characteristics, root development patterns, or yield. Acharya (2017) summarized the results of field demonstration trials comparing RT or ZT in rice, wheat and maize from different locations in the mid-hills and the Terai. They observed that the yield of rice under DSR was reduced when established using RT or ZT compared to CT, though production cost in all crops was consistently lower in the former than in the latter. Karki et al. (2014b) concluded that a significant reduction in

Table 8 Average annual losses of soil, soil organic carbon (SOC) and major nutrients in sediments from different treatments in a mid-hill district in western Nepal.

	Soil and soil organic carbon loss (kg ha^{-1} yr^{-1})		Nutrient loss (kg ha^{-1} yr^{-1})		
Experimental treatment	**Soil loss ± SE**	**SOC ± SE**	**Total N ± SE**	**Avg. P ± SE**	**Exch. K ± SE**
Farmers' conventional practices	1222 ± 45.5	25.5 ± 12.3	5.3 ± 2.1	0.1 ± 0.01	0.12 ± 0.03
Reduced tillage practices	1017 ± 36.3	17.5 ± 6.8	3.9 ± 1.5	0.1 ± 0.01	0.09 ± 0.04
Commercial vegetable production	1265 ± 43.1	24.5 ± 11.4	5.6 ± 2.1	0.1 ± 0.02	0.11 ± 0.05

SE indicates standard error.

Adapted based on data from Tiwari, K.R., Sitaula, B.K., Børresen, T., 2009a. Effects of soil and crop management practices on yields, income and nutrients losses from upland farming systems in the Middle mountains region of Nepal. Nutr. Cycl. Agroecosys. 12, 26-41. https://doi.org/10.1007/s10705-009-9289-0.

production cost and increase in income could result without any yield penalty from CA compared to conventional practices in a maize-rapeseed rotation in both the mid-hills and Terai. Laborde and McDonald (2019) reported that after 2 years of conversion from conventional tillage to CA in maize-rapeseed and maize-wheat rotational systems, the mean weight diameter of dry aggregates (0–5 and 5–10 cm depths) was greater (by 45% and 24%, respectively), soil sorptivity lower, and BD (measured at the 0–15 cm depth) greater in CA than the CT. Maize yields were either similar to, or lower than, CT practices, but there were no effects on the ensuing rapeseed or wheat crops. These findings demonstrate that during the initial years of transition from conventional to a CA based crop management system, soil physical properties may improve but crop yield could either decrease or remain stable in the mid-hills of Nepal. As such, the benefits CA appear to be largely oriented towards improving environmental outcomes, and the efficiency and profitability of crop production. Additional management interventions are conversely likely to be needed to increase yield.

In the Terai, Ghimire et al. (2011) reported that soils under a rice-wheat rotation sequestered significantly a higher amount of SOC at 0–50 cm soil depth, with more pronounced effect at 0–15 cm depth under no-tillage compared to CT. Addition of crop residues to no-tillage plots resulted in improved organic carbon sequestration, but there was no effect of N management on soil carbon. Acharya (2017) reported that grain yields of wheat and rice in Terai performed inconsistently under RT and CT. Production cost was nonetheless consistently lower, and benefit-cost ratio consistently higher, under RT than under CT. Devkota et al. (2019) conducted farmer-participatory on-farm experiments in an irrigated CA-based rice-wheat rotation from 2011 to 2017 in the western Terai. Both DSR and zero-tilled wheat produced similar or higher grain yield with lower production costs, higher water productivity, and higher net profit than conventionally tilled wheat. Their results also demonstrated that when early rainfall is deficient, the direct seeding of rice without tillage permits timely establishment, which can boost yield and maintain yield stability across years. DSR followed by zero-tilled wheat increased yield, reduced production cost and increased net profit, while also reducing the risk of terminal heat stress in wheat as a result of early establishment, compared to conventional tillage in rainfed locations or areas with limited irrigation facilities. Karki et al. (2014a) also concluded that, compared to conventional tillage, CA could significantly reduce production cost and increase income without any yield penalty in a maize-wheat rotation in the central Terai.

Islam et al. (2019) suggested that rice yields under rice-wheat, rice-maize, and rice-lentil cropping systems were not significantly different between conventional tillage and CA, but there was a significant yield gain of around 5% in wheat, maize or lentil in Nepal's Dhanusha and Sunsari districts in the central and eastern Terai, respectively., CA also reduced irrigation water requirements for wheat and maize. This resulted in increase in total water productivity by greater than 26%; when considering both crops in rotation, irrigation water productivity increased by greater than 25% and greater than 10%, respectively.

Summarizing available research, Dixon et al. (2020) concluded that CA can improve food production, increase energy and water use efficiencies. CA was were also suggested to have potential additional socioeconomic benefits for smallholder farm households. Dixon et al. (2019) also identified areas for further development of research methods associated with CA. These included increased systems research in agronomy, improved weed management, alignment with the principles of climate smart agriculture, behavioral science insights into farmers' decision-making regarding adaptation and adoption of tillage and crop establishment technologies, as well as an understanding of the role of social capital and institutions in technology targeting, scaling, and regional food systems policies.

5.3.2 Nutrient management

Challenges to improved nutrient management in Nepal are best considered within a cropping systems context. For example, in the low-input rice-wheat and rice-maize rotations systems of Indo-Gangetic Plains, which include the Terai, the nutrition of all crops is largely based on indigenous N supply (Timsina and Connor, 2001; Timsina et al., 2010). With the onset of rains during the dry to wet season transition, a period of 6–10 weeks, large amounts of nitrate can accumulate in the soil. This developing pool of N is subject to potential losses and nitrous oxide emissions upon soil saturation (Becker et al., 2007; Pandey and Becker, 2003), and is a common problem. Management interventions during this period should aim to avoid losses of water and native soil N, and are discussed in Section 6.4.2.

In addition to the management of nitrate prior to tillage and crop establishment, findings from three rotational (rice-wheat, maize-millet and upland rice-black gram) experiments across six sites in eastern and western mid-hills of Nepal showed that the combined application of manure in combination with inorganic fertilizers can result in higher productivity and larger economic benefits than application of either one alone (Pilbeam, et al., 1999), underpinning the importance of integrated soil fertility management approaches in Nepal. In another maize-millet rotation at two mid-hill locations in eastern and western Nepal, Pilbeam et al. (2002) measured the recovery of ^{15}N-labeled urea applied as a top-dressing to maize at three rates (11.3, 22.5, 45.0 kg N ha^{-1}). Grain and straw yields of maize were greater following the application of fertilizer either alone or in combination with manure, rather than manure lone. Little (less than 25%) of the applied fertilizer was recovered in the maize crop, with just 3% more recovered by the subsequent millet crop. On average, 58% of the applied fertilizer was found in the 0- to 60-cm soil layer at maize harvest, mainly in non-mineral N pools.

In another study of irrigated cropping systems in the in Jikhu Khola Watershed in a mid-hill region in western Nepal, Westarp et al. (2004) reported a significant increase in available soil P and soil pH, and a significant decline in exchangeable soil K and base cation content in 2000 compared to 1994 as a result of policies favoring unbalanced fertilizer use and the introduction of potatoes, tomatoes in place of pre-monsoon season fallowing. In contrast, rainfed sites had large surpluses of N, P, and K, with significant increases in soil K, base saturation and available soil P over the same period. These results demonstrate the need to develop sustainable strategies to increase K and reduce P for irrigated systems, and reduce N, P and K for rainfed systems, to maintain nutrient balances in the mid-hills of Nepal.

Long-term experiments are useful in understanding the trends in the performance of cropping systems, and to accordingly develop improved management practices (Ladha et al., 2003; Timsina and Connor, 2001). The rice-wheat rotation is arguably the region's most widely studied cropping pattern. A number of long-term trials have been established to monitor and examine yield trend patterns and soil physical and chemical properties across the Indo-Gangetic Plains (Ladha et al., 2003; Timsina and Connor, 2001). Across a suite of long-term trials examined, Ladha et al. (2003) reported that depletion of soil C, N, Zn and P, delayed planting, and decreased solar radiation and increased minimum temperatures, were among the major causes of yield decline for both crops in this region. In a long-term trial established on a silty loam to silty clay loam soils at Bhairahawa, in the western Terai, both rice and wheat yields were lower than their attainable yields due to lower nutrient (especially K) availability (Regmi et al., 2002b). Both crops responded to P and K addition, but wheat response to the latter was substantially higher, indicating that native K availability was lower for the wheat crop. Wheat yield declined in all treatments except when farmyard manure was applied, indicating the role of organic matter additions in sustaining yield.

In another long-term rice-wheat rotation trial at the same site, Regmi et al. (2002a) reported that soil K depletion and inadequate K fertilization were primary reasons for declining crop yields and nutrient balances. Similar trials under rice-wheat rotations on an Inceptisol, loamy sand soil at Parwanipur in Central Terai, however showed that both rice and wheat yields responded to N but not to P, K, Zn and S application (Gami et al., 2001). This indicates that other than N, soil supplies of these nutrients were non-limiting. Across crops, apparent N and P balances were positive in treatments with N, P, and K, as well as and farmyard manure, but the observed K balance was negative in all plots except those in which farmyard manure was applied to both rice and wheat. In another long-term trial in a rice-wheat rotation on a silty clay loam at Sunsari in eastern Terai, the application of 10 t of farmyard manure ha^{-1} and balanced application N, P, and K fertilizers increased SOM and maintained wheat yield and soil pH over 10 years (S.R. Shrestha, 2019, personal communication).

Negative K balances and K deficiencies in rice-wheat and rice-maize rotations however appear to be widespread throughout the Indo-Gangetic plains, due in large part to the lack of consistent K application by farmers (Ladha et al., 2003; Panaullah et al., 2006; Singh et al., 2018; Timsina et al., 2013). Ladha et al. (2003) reported that in contrast to trials in Nepal where wheat yields declined at a more rapid rate than rice yields, in most other trials across the region, rice yields declined more quickly than wheat yields. Although the reasons for yield decline were primarily location-specific, soil K depletion was a general cause of declining rice yield in over 90% of the observed long-term trials. Applied fertilizer K rates were not sufficient to sustain a neutral K input–output balance. Declining yield trends in rice-wheat rotations suggest scope for yield improvement through continued monitoring and the revision of nutrient management recommendations for component crops and systems.

In addition to long-term experiments, observations in farmers' fields of improved fertilizer application technologies can be useful. Park et al. (2018) demonstrated that use of a simple, low-cost, chest mounted seed and fertilizer drill resulted in significant N and P use efficiencies in wheat in Nepal and in Bihar state within India. In addition, within field application variability associated with manual broadcasting could be overcome with the use of this relatively simple and low-cost implement. Efforts are ongoing to increase the popularity of these 'knapsack spreaders', although the relative ease of manual broadcasting, slow market development, and continued lack of awareness on the importance of even seed and fertilizer distribution has limited uptake (CSISA, 2020).

Improved understanding of farm and watershed-level nutrient balances are likely to be more useful than plot or field-level assessments, and if clearly articulated, could aid in land use planning and policy making decisions. There are however relatively few studies with such assessments. Pilbeam et al. (2000) concluded that for a hypothetical one hectare land holding sub-divided into two-thirds rainfed hillside and one-third irrigated terraces in a mid-hill location, it was possible to maintain an adequate N balance given adequate nutrient cycling. Forage fed to livestock and the subsequent application of manure to crops was the major pathway for N flow within this farming system. Use of tree fodder and forage from nearby forest areas, and grasses from terrace risers used as animal feed resulted in net N movement from non-agricultural to agricultural land. In a series of on-farm experimental and long-term simulation experiments using DSSAT in maize in the mid-hill district of Palpa, Devkota et al. (2016) showed that (a) degraded soils in the mid-hills of Nepal respond favorably to macronutrient fertilizers—even at high rates, (b) balanced fertilization is necessary to optimize returns on N investments, but these must be weighed against additional costs, (c) OPVs of maize can benefit from investments in fertilizer, albeit at a partial factor productivity of N that is 36–47% lower than for hybrids, and, consequently (d), where farmers can afford investments in seed, hybrids can be an effective mechanism to achieve a higher return on fertilizer, even when modest rates are applied. Most hybrids in Nepal are however grown as a cash crop, with maize sold to mills to produce poultry feed (Freshley and Delgado-Serrano, 2020), while OPVs tend to be consumed by households as a source of food (Freshley and Delgado-Serrano, 2020). Although when coupled with good agronomic practices, the use of hybrids has been showing to be profitable in Nepal (Devkota et al., 2016), conversion from OPVs to hybrids would require that farmers are willing to take risks and engage with market rather than subsistence production. Farmers would also need to be able to afford initial investments to access to higher-priced hybrid seeds and fertilizer, as well as being able to access markets– both for maize sold and for inputs purchased.

5.3.3 Management of soil acidity

As described in Section 3.3.1, many of the soils in both the hills and Terai are acidic. Soil acidity can also increase when nitrogenous fertilizers are applied in excess without associated SOM management (Tripathi, 1999a,b). Tripathi (1999a) reviewed the extent and distribution of acid soil and its management in Nepal. Tripathi (1999a,b) reported the existence of acid soil tolerant local and improved varieties of maize, wheat, soybean, and upland rice varieties in different regions of Nepal. He also indicated a positive yield response to different doses of agricultural lime ($CaCO_3$), farmyard manure, and P fertilizers, both independently or in combination on the acidic soils of the eastern, western and central regions of Nepal. When agriculture lime was applied to acidic soil, Tripathi (1999a,b) also suggested that only 40–45% of it is utilized by the first crop and the remaining 55–60% utilized by succeeding crops. In a study on three hill research farms (Khumaltar Farm in Lalitpur, Kakani Farm in Nuwakot and Kavre Farm in Dolakha) in central Nepal, the application of $CaCO_3$ at 2–3 t ha^{-1} to maize increased soil pH and maize yield, and also had a residual effect on the succeeding wheat crop in a maize-wheat rotation in the first year of application. Further residual effects were also found for both crops in the second year of rotation (Tripathi, 1999a). The author concluded that in Nepal, $CaCO_3$ should be applied and incorporated into the soil every 3–4 years. The Government of Nepal has established $CaCO_3$ industry in Jogimara in Dhading district to provide lime to farmers affected by acid soils.

In addition to $CaCO_3$, research has also sought to identify alternative mechanisms to reduce soil acidity. Schreier et al. (1998) carried out an experiment on a very degraded acid soil of Jhikhu Khola watershed, Kavre with the use of lime and manure, obtaining significant improvement in the biomass production of nitrogen fixing trees and native grasses. Studies in the Philippines (cf. Tripathi and Dacayo, 1988) showed that application of rice hull ash at 10 t ha^{-1} increased pH of acid soils by releasing the availability of fixed P from Fe and Al. Rice hull application also increased dry matter of *Sesbania rostrata* grown after rice, as well as the yield of the ensuing rice crop. In addition, Ghimire and Bista (2016) used farm observations from Nuwakot and Chitwan in the mid-hills of Nepal to demonstrate that in opposition to continuous monoculture, crop species diversification was associated with reclamation of acid soils.

5.3.4 Supplementary and improved irrigation management

Supplementary irrigation refers to water use regimes where irrigation provides less water to overall crop water use than does precipitation (Reinders, 2020). Due to Nepal's erratic rainfall patterns, supplementary irrigation supports farmers in timely crop establishment and in overcoming moisture stress during water sensitive crop growth stages (Devkota et al., 2019; McDonald et al., 2006a,b). As agricultural droughts are predicted to intensify in the future, the importance of supplementary irrigation will increase; farmers in the Terai are already adapting to these changes by investing increasingly in groundwater irrigation (Paudel et al., 2020c; Urfels et al., 2020, 2021). Singh et al. (2019) demonstrated a non-linear yield response to the timing of rice establishment in the neighboring Indian state of Bihar, where yield levels drop by ca. 70% if a critical threshold of timely crop establishment is passed, highlighting that supplementary irrigation is critical for years in which the monsoon arrives late. Urfels et al. (2020, 2021, in review) further show that the suction depth limit of ca. 6–8 m for the commonly used centrifugal pumps, in some places restrict farmers' ability to use supplementary groundwater irrigation for timely establishment before monsoon rains replenish the aquifers in the Terai. This has important cascading effects for the subsequent dry season crop (Newport et al., 2020; Shah et al., 2020). As most canal irrigation schemes rely on the monsoon onset to increase stream water flows, the use of submersible pumps that do not have a suction depth limit, directly sown rice, or shorter duration rice varieties present potential options for overcoming this barrier. The cultivation of alternative crops could also address these issues, but the cultural importance of rice production and challenges in growing other crops during the monsoon render rice the most feasible option in lowland soils or soils prone to waterlogging. Furthermore, McDonald (2006a,b) found that dry season crops tend to significantly benefit (1.4 t ha^{-1}) from irrigation during planting.

Knowledge and infrastructural gaps—rather than water availability—limit in-season irrigation of cereal crops in Nepal's Terai. In a meta-analysis, Carrijo et al. (2017) consider alternate wetting and drying (AWD) practices in rice and show that supplementary irrigation in rice can achieve yield levels comparable to continuously flooded irrigation. The same authors also found that AWD with severe water stress (−20 kPa) led to rice yield reductions of 22% on average, especially in acidic and/or soils with low soil carbon. The numbers resonate well with Nepal, where severe water stress is the norm in precipitation deficit years as high rental rates for pumping equipment, late scheduling, and insufficient infrastructure tend to limit timely irrigation (Foster et al., 2019; Urfels et al., 2020, 2021). To study these issues, we simulated the attainable yield of rice with 150 kg N ha^{-1} under rainfed and partially irrigated (with 50 mm at −10 kPa) in eight Terai locations using the ORYZA3 rice growth model developed by Bouman et al. (2001). Between 1970 and 2015, our analysis indicates that the attainable rice yield increased by 2% when irrigated, but decreased by 21% under rainfed conditions (Fig. 17). This suggests that unreliable irrigation not only increases climate risk, but also precludes farmers from benefitting from CO_2 enrichment under climatic change.

Soil cracking when rice fields reach water deficits is a largely neglected aspect of supplementary irrigation in Nepal, although it has shown to dramatically impact field water dynamics elsewhere—especially in rice-based production systems (Tuong et al., 1996). Anecdotal evidence suggests that soil cracking impacts supplementary irrigation in Nepal, albeit its occurrence, effects and treatment remain largely unknown, representative of a potentially important research gap. Similarly, dry winter season wheat cultivation can largely benefit from increased irrigation rates, as rainfall is generally insufficient to cover crop water requirements (Shrestha et al., 2013a).

Using the AquaCrop model, Shrestha et al. (2013a) reported that for summer monsoon season rice and maize in Chitwan, central Terai, improved soil fertility management was more important than water management for obtaining high system level yields. Conversely, for winter and spring season wheat and maize, partial or full irrigation together with fertilizer application was more important. In the summer monsoon season, rice and maize yields could be increased by up to 65% and 58%, respectively, with improved fertilizer management. Conversely, considering wheat and spring maize, yields could respectively be increased by up to 197% and 100%, respectively, with improved irrigation management. Shrestha et al. (2013b) compared water and fertilizer management strategies for wheat

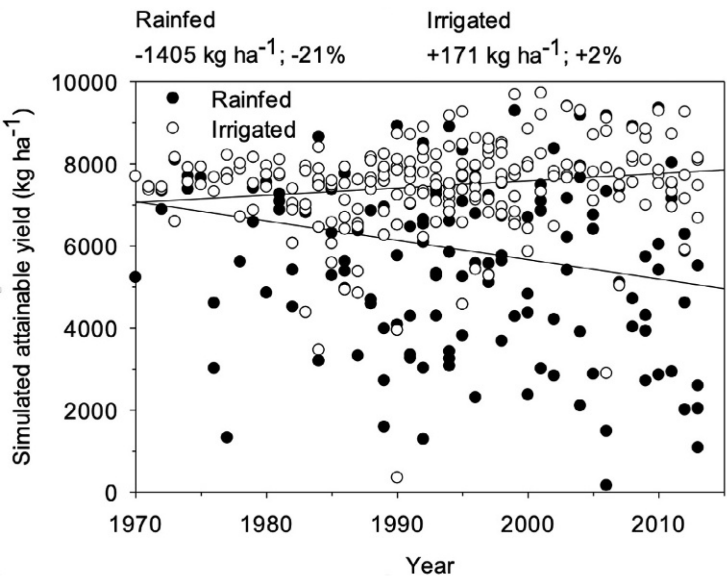

Fig. 17 Simulated attainable yield of rice under rainfed (no supplementary irrigation) and irrigated (50 mm irrigation when soil moisture at 10 cm soil depth depletes to −10 kPa) conditions in eight Terai districts (Sunsari, Dhanusha, Bara, Chitwan, Rupandehi, Dang, Banke, Kailali, Kanchanpur) using multiple soil profile and long-term weather data from district meteorological stations using the rice growth model ORYZA3. *Data from Devkota, K.P., 2017. Use of ORYZA-3 simulation model for rice productivity assessment in Teri districts of Nepal. In: Paudel, M.N., Bhandari, D.R., KHanal, M. P., Joishi, B.K., Acharya, P., Ghimire, K.H. (Eds.), Rice Science and Technology in Nepal. Crop Development Directorate (CDD), Hariharbhawan and Agronomy Society of Nepal (ASoN), Khumaltar, pp. 623–629. http://cddnepal.gov.np/downloadfile/Rice_science_and_technology_1512106674.pdf.*

and spring maize for three soil types (loamy, sandy loam and silty clay loam) in nearby farmers' fields also in Chitwan, central Terai in the same location. In wheat, a single irrigation application (equivalent to roughly a quarter of net irrigation requirement) increased yield by 28–86%, while two irrigation applications (a third of net irrigation requirement) increased by 39–105%. In spring maize, application of deficit irrigation of 1/4th of net irrigation requirement increased yield by 15–77% across different fertilizer application levels and soil types. Since rainfall was almost negligible in the growing season of spring maize, the differences in maize yield for various soil types were less pronounced than for wheat. Findings of these studies suggested that for fertilizer application below 50% of the nationally recommended fertilizer rate, deficit irrigation application of a quarter of net irrigation requirement was sufficient, but for application above 50% recommended fertilize rates, irrigation water equal to or higher than a third net irrigation requirement would be necessary to achieve stable yields.

5.3.5 Pest, disease and weed management

It has been widely recognized that since the start of Green Revolution in 1970s, crop yields have substantially increased land use efficiency in developing countries (Davis, 2003). At the same time, the Green Revolution has had a number of unintended and secondary negative consequences, for example the exacerbation of weed, pest and disease problems (Pingali, 2012). Since the uptake of Green Revolution technologies in Nepal, pesticide application has begun to become more common, with more than 2200 pesticides (inclusive of insecticides, fungicides, herbicides, and rodenticides) now registered (Adhikari, 2017).

The manifestation of these Green Revolution second generation problems has been documented in long-term experiments in Nepal's rice-wheat systems. In a long-term trial of a rice-wheat rotation Bhairahawa in Western Nepal Terai, the interaction of increasing K deficiency with *Helminthosporium* spp. leaf blight (spot blotch and tan spot) was previously considered one of the key factors limiting wheat yields (Regmi et al., 2002b). However, leaf rust (*Puccinia triticina*) is also now common in wheat grown in the hills and Terai, with concentrations in eastern Nepal. Observations by CIMMYT and NARC have also indicated that stripe rusts (*Puccinia graminis*) are increasingly found in the mid-hills, with *P. graminis* also appearing to move into the eastern Terai (CIMMYT, 2020).

Turcicum leaf blight (*Exserohilum turcicum*) has become highly problematic in intensified maize production systems in the cooler mid-hills of Nepal, while insect pests are more of a challenge in the lowland Terai than in the hills (Paudyal et al., 2001). This is likely a consequence of less biodiverse landscapes with refugia for predators and parasitosis, and the higher temperatures of the Terai that allow the rapid development of overlapping arthropod generations. The cultivation of monsoon season maize followed by winter season maize also appears to favor gray leaf spot (*Cercospora zea-maydis*), a recently introduced but economically important disease causing significant yield losses and underscoring the importance of diversified rotations to limit disease pressure (Manandhar et al., 2011). A one-year rotation away from maize, followed by tillage, has been recommended to prevent disease development in the subsequent maize crop in the United States (Wise, 2010); similar tactics may hold promise in Nepal where double cropping of maize is practiced.

In addition to these issues, cereal-based agroecosystems in Nepal also face threats from new and emerging pests. Key among these concerns is the Lepidopteran Noctuid, Fall Armyworm, (*Spodoptera frugiperda* J. E. Smith) (FAW), a polyphagous pest but with strong preferences for maize. FAW was first officially documented in Nepal in 2019 following its migration from southern India, where it was observed for the first time in Asia in 2018 (Bajracharya et al., 2021). Since then, it has been observed as a pest of maize and to lesser extent other plant species, resulting in calls for the development of integrated pest management techniques appropriate for this species (Bhusal and Bhattarai, 2019). Yet as a relatively new and invasive pest, farmers' knowledge of management techniques is limited, as is knowledge of how the patterns of FAW attack may emerge over time before natural enemy suppression kicks in to regulate populations in Nepal. Gc et al. (2019) for example noted that given Nepal's relatively unique range of elevation and differing temperature and precipitation patterns in which maize is grown, a wide geographic range of studies will be needed to identify context-specific management techniques in response to the observed population dynamics of this pest.

Invasive species that threaten the stability of agroecosystems is not limited to arthropods. The weed *Parthenium hysterophorus* L. is highly competitive, and has a wide association with cereals, including rice, wheat, and maize. It can generate more than 5000 seeds m^{-2}, and has become a common problem in Nepal (Adkins and Shabbir, 2014). In the wheat phase of rice-wheat rotations, in particular, the gramineous *Phalaris minor* has been a long-standing concern in Nepal (Lamsal and Khadka 2019; Ranjit et al., 2009). Research conducted in adjacent areas in India has shown that the use of zero tillage and alternative herbicides can aid in reducing competition with this species (Malik et al., 2000). The coupling of weed competitive wheat genotypes with zero tillage may lend additional advantages (Chauhan et al., 2001). These examples point to the importance of integrated weed management techniques that combine cultural practices with competitive cultivars, with the inclusion of chemical control when and where necessary.

6. Discussion

This review has identified several critical agricultural development challenges and research gaps in cereal-based farming systems in the hills and Terai of Nepal. Many of these challenges and associated research gaps are also similar to and will have implications for the other countries of South Asia that share portions of the Himalayan mountain and hill ranges.

6.1 Land-use challenges

As with other countries in the region, farmland fragmentation, urbanization, land fallowing, and abandonment were identified as key issues in the Terai (ADS, 2015; MoLRM, 2015; Niroula and Thapa, 2005; Uddin et al., 2015). Abandonment of farmlands is more of a concern in the hills, where land terraces may not be maintained (Naz and Romshoo, 2012; Shrestha, 2014; Yamaguchi et al., 2016). Khanal (2018) and Chaudhary et al. (2020) also recognized that in addition to increased erosion risks, farmland abandonment is associated with the loss of culturally important agricultural and social traditions.

6.1.1 Land-use changes

Since the 1950s, Nepal has implemented a suite of land use reform policies (Table 9). Recent changes since the adoption of the 2015 constitution have also resulted in the decentralization of land and agricultural administration, including land redistribution. While increased municipal and provincial autonomy presents new opportunities for improved land management, it also presents challenges in coordination and the generation of insights from land-use change and monitoring efforts. Examples of policy tools that could be deployed to address farmland fragmentation, urbanization, land fallowing, and abandonment include land pooling, land classification, zoning, and tax or incentive-based discrimination to limit fragmentation and conversion from agricultural to other less productive land uses (MoLRM, 2015). Planning to reduce deforestation in both hills and Terai should also be integrated with these efforts. Agricultural policy research is needed to examine the outcomes of these interventions to increase learning and improvements in land use and management policies.

6.1.2 Land degradation

In Nepal's hills, land abandonment is associated with increased erosion risks (Tarolli et al., 2014). These include overland, rain splash, rill, soil creep erosion and collapse of terraces, in addition to SOM and nutrient losses. As land abandonment in the hills is linked to the larger process of rural-out migration that affects much of South Asia but Nepal in particular (Jaquet et al., 2019; Lipton, 1980; Maharjan et al., 2013a), practical and labor-saving methods are needed to maintain terraces and aid in agricultural activities (Tarolli et al., 2014). As larger tractors are difficult to operate in Nepal's hills and

Table 9 Summary of major land management challenges and opportunities in Nepal's cereal-based farming systems.

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
Land use changes	Farmland fragmentation, urbanization, land fallowing and abandonment	• Land reform policy research to increase learning from the problems arising from the Forest National Act (1957), the Land Act (1964), the Land Ownership Registration Act (1968), Land Acquisition Act (1977), the Land Revenue Act (1977), the Agriculture Perspective Plan (1995–2015), the National Agriculture Policy (2004), the National Adaptation Program of Action (2010) and the National Land Use Policy (2012), and current land and administrative restructuring under the 2015 constitution • Land use zoning to conserve agricultural land • Land classification zoning and tax or incentive-based discrimination to limit fragmentation and conversion from agricultural to other less productive land uses. • Scale-appropriate farm machinery	Gartaula et al. (2012), Jaquet et al. (2019), KC and Race (2019), Niroula and Thapa (2005), Mango and Hebinck (2016), MoLRM (2015), Paudel et al. (2013), Paudel et al. (2019b, 2020a,b,c), Tiwari et al. (2004), Schwab et al. (2015), Uddin et al. (2015)
Land degradation	Overland, rain splash, rill and soil creep (terrace collapse) erosion, SOM and nutrient losses through erosion and leaching, land abandonment (particularly of terraces)	• Integrated development planning to reduce deforestation • Land terracing • Multiple cropping and maintenance of a living soil cover • Integration of farmers' indigenous with scientific knowledge • Use of retention walls • Contour plantings in agroforestry systems • Alley cropping • Manuring and mulching • Use of lightweight, low-cost and affordable machinery for terrace land preparation	Acharya et al. (2007), Atreya et al. (2005), Ba et al. (2019), Brown and Shrestha (2000), Bashagaluke et al. (2018), Chalise et al. (2019), Chapagain and Raizada, 2017, Chaudhary et al. (2020), CSISA (2019), Gardner and Gerrard (2003), Gardner et al. (2000), Islam et al. (2019), KC and Race (2019), Khanal (2018), Khanal and Watanabe (2006), Mango and Hebinck (2016), Pandit and Balla (2006), Paudel et al. (2019b), Paudel (2016a,b), Paudel and Thapa (2001), Partap and Watson (1994), Schreier et al. (1998), Sherchand and Gurung (1995), Schwab et al. (2015), Shrestha (1997), Tarolli et al. (2014), Tiwari et al. (2009a,b)

mountains, farmers tend to make use of locally made agricultural tools draft animals, in addition to human labor, for land preparation, plowing, and other farm operations (Tiwari et al., 2004). Chapagain and Raizada (2017) suggested terrace intensification using agroecological approaches and lightweight, low-cost, and affordable machinery that can enhance productivity and reduce drudgery experienced by women. These could provide a partial answer and agronomic strategy to address the challenges of terraced farming, given the high rate of out-migration and loss of labor from Nepal.

Activities recently conducted by the CIMMYT under the CSISA program included the commercial introduction of mini-tillers, which are small and light-weight 5–7 hp land preparation machines that can be more easily transported up and down terraces in hilly environments (Paudel et al., 2019a). Evidence indicates that alongside the use of these machines by individual farmers to prepare land on their own terraces, an economy of service provision whereby other farmers hire machinery owners to prepare land is beginning to emerge (Paudel et al., 2019a). Importantly, the adoption of mini-tiller services also appears to be larger among more food-insecure households than those with reliable food supplies, indicating the appropriateness of this technology and service provision arrangements to increase access to land preparation on terraces (Paudel et al., 2020a,b,c). Research to monitor the use of scale-appropriate farm machinery in Nepal's hills and how access to machinery addresses not only labor but also land conservation and management constraints therefore remains an important priority.

6.2 Environmental challenges and opportunities

Key environmental challenges identified in this review include restoration of soil fertility, climate variability and change, and the maintenance of ecosystem services and environmental quality (Table 10).

6.2.1 Maintenance and restoration of soil fertility

Low levels of soil nutrient reserves, nutrient mining, and soil acidity are key issues in Nepal (Acharya et al., 2007; Brown and Shrestha, 2000; Dawadi and Thapa, 2015; Gardner et al., 2000; Gardner and Gerrard, 2003; Partap and Watson, 1994; Schreier et al., 1998; Tripathi 1999a,b; Tiwari et al., 2009a). Soils to be low in P in the eastern Terrai, while K mining has become a concern where residues are consistently removed from farmlands (Dawadi and Thapa, 2015). While efforts to develop digital soil maps in Nepal are nascent (Pandey et al., 2018b), comprehensive and high-resolution soil maps are an urgent research need that could aid in soil fertility management and

Table 10 Summary of environmental challenges and opportunities in Nepal's cereal-based farming systems.

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
Maintenance and restoration of soil fertility	Low soil nutrient reserves and nutrient mining, particularly at lower altitudes, soil acidity, low P2O5, particularly in the eastern Terai, low K in the Terai	• High-resolution digital soil mapping (acidity and nutrient stocks) to aid in more precise soil fertility management recommendations • Include secondary and micronutrients in soil fertility management recommendations • Precision nutrient management, replenishment of extracted nutrients (with emphasis on K) • Development and use of compound and blended fertilizers • Increase efforts to quality control fertilizer materials • $CaCO_3$ and organic matter application (research to validate and the extension of rice hull ash and sugarcane waste amendments) • Policies an d markets that improve the distribution, availability and affordability for $CaCO_3$ • Increased studies to quantify the distribution of soil secondary and micro-nutrients (B, S, Ca, Mg, and Zn)	Andersen (2007), Bajracharya et al. (2007), Bajracharya and Sherchand (2009), Bajracharya et al. (2007), Devkota et al. (2015), Carson et al. (1986), Ghimire and Bista (2016), Hoyum (2012), NSAF (2019), Pandey et al. (2018a,b), Paudyal et al. (2001), Schreier et al. (1998), Takeshima et al. (2016), Takeshima and Bhattarai (2019), Tripathi and Dacayo (1988), Timsina (2001), Tiwari et al. (2009c), Turton et al. (1996), Tripathi (1999a)

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Table 10 Summary of environmental challenges and opportunities in Nepal's cereal-based farming systems.—cont'd

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
	Poor soil organic matter (SOM) reserves	• Enhance nutrient and carbon cycling through livestock integration • Couple poultry production industries to farms by returning manure • Reduce distances from livestock sheds and poultry houses to farm fields • Build soil organic matter reserves through integrated and ecosystem-based soil fertility management • Maintain crop residues as mulches • Use of agroforestry species	Adhikari and Dahal (2015), Bajracharya, (2007), Bajracharya and Sherchand (2009), Bajracharya et al. (2007), Baral et al. (2020), Khatiwada et al. (2013), Maskey et al. (2000a,b), Pilbeam et al. (2000), Pokhrel and Virarahghavan (2005), Sherchand (1989), Tirol-Padre et al. (2007)
	Limited advances and sub-optimal integration of biological N fixation (BNF)	• Strategic integration of biological nitrogen fixation in crop rotations and in rice • Development of markets for products of appropriate Rhizobium spp., with attention paid to overcoming preservation and transport constraints • *Re*-invigorate research on BNF in Nepal	Adhikari and Dahal (2015), Bhattarai (1987), Maskey et al. (2000a,b), Sherchand (1989)
Climate variability and change	Increasing temperatures, particularly in western Nepal and Terai, terminal heat stress affecting wheat in the Terai, and to a lesser extent in other cereals	• Coupled crop and climate change modeling • Development and use of abiotic stress tolerant varieties • Early sowing to avoid terminal heat stress in wheat • Coupling of long duration wheat cultivars with early sowing • Climate-coupled agricultural advisory services • Supplementary irrigation	ADS (2015), APN (2005), Bannayan et al. (2011), Bocchiola et al. (2019), Bhatta et al. (2014), Bocchiola et al. (2019), Chalise et al. (2017), Hossain et al. (2018), Kukal and Irmak (2018), Palazzoli et al. (2015), Paudyal et al. (2001), Poudel et al. (2014), CSISA (2017, 2019), Dixon et al. (2019, 2020)

	Precipitation variability (particularly in western Nepal and the Terai), late monsoon onset, within monsoon season drought	• Agriculturally focused climate information services (CIS) • Take stock of farmers' indigenous knowledge on precipitation patterns; apply knowledge in the design of CIS • High-resolution precipitation forecasts • Improved resolution and skill in weather, sub-seasonal, and seasonal forecasts • Drought monitoring and forecasting • Link the Department of Hydrology and Meterology formally and the Nepal Agricultural Research Council formally in agricultural climate services research • Supplementary and 'life-saving' irrigation • Crop insurance programs to aid in managing losses and damage	Chalise et al. (2017), CSISA (2017,2019), Ensor et al. (2019), Khanal et al. (2018), Raut et al. (2010), Sigdel and Ikeda (2012), Tiwari et al. (2008a), Sapkota and Devkota (2019), Shrestha et al. (2018), Urfels et al. (2020, 2021)
	Gradual loss of glacier-ice reserves, reduced stream and river flow in the winter, flooding in the Terai, precipitation variability (and high intensify but brief rainfall) affecting groundwater recharge and availability, heterogeneously distributed aquifers	• Cultivation of less water demanding and potentially profitable crops (e.g., maize) as an alternative to rice • Limitations on civil infrastructure development (e.g., road construction or diversion of springs) • Crop insurance programs to aid in managing flooding losses and damage • Integrated up and downstream planning and management to increase environmental flows and replenish groundwater • Comprehensive groundwater aquifer mapping and monitoring	Bharati et al. (2014), Chaulagain (2009), Doll (2002), Hasan et al. (2019), Nyakundi et al. (2015), Panda et al. (2019), Pandey et al. (2019, 2020), Paudel and Duex (2017), Pariyar et al. (2018), Qamer et al. (2020)

Continued

Table 10 Summary of environmental challenges and opportunities in Nepal's cereal-based farming systems.—cont'd

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
Crop intensification, ecosystem services and environmental quality	Increased agrochemical use, intensive horticultural practices, greenhouse gas emissions, intensive tillage and reduced soil physical structure decreasing soil physical quality, shifts in the abundance and intensity of pest attack	• Deliberate agricultural crop intensification planning and policies to account for potential negative environmental externalities • Agroecological management of pests • Soil solarization • Reduced and zero-tillage systems • Limiting the timing and application of agro-chemicals to synchronize with crop need and to avoid leaching and water contamination risks • Farmer educational programs highlighting the importance of ecosystem services	Brown and Shrestha (2000), Culman et al. (2006), Dahal et al. (2009), Pandit and Balla (2006), Raut et al. (2010, 2011), Timsina and Connor (2001)

restoration decisions. Similarly, inclusion of secondary and micronutrient management recommendations and the development of compound fertilizers to meet site- and crops-specific nutrient needs are priorities. These efforts should be merged with integrated soil fertility management that combines organic matter and synthetic fertilizer application (Ghimire and Bista, 2016; Schreier et al., 1998), alongside extension efforts that emphasize K recycling. Research is well established in Nepal that indicates the use of agricultural lime can aid in correcting soil acidity (Schreier et al., 1998; Tripathi, 1999a,b). Despite the production of $CaCO_3$ in Dhading district, and due to the remoteness and rugged landscapes of hills and mountains, farmers' access to agricultural lime remains a challenge in Nepal. Poor access is also partly due to a lack of supportive policies and markets that improve distribution, availability and affordability. Research into additional alternative mechanisms to manage acidity is therefore needed.

Poor reserves of organic matter are a related concern (Dijkshoorn and Huting, 2009), particularly in the intensively cultivated soils of the Terai (Pandey et al., 2018b). As a result, enhanced nutrient and carbon cycling through the integration and close placement of livestock and poultry sheds to farm fields are potential options, as are the recycling of crop residues and agroforestry (Devkota et al., 2006; Khatiwada et al. 2013; Pokhrel and Virarahghavan, 2005; Schwab et al., 2015). Use of animal wastes as soil amendments however requires improvements, as most manures are either semi- or unprocessed, which can lead to volatilization losses.

Lastly, BNF is a significantly under-researched area in Nepal, although a number of options have been documented (ARS, 1994; Adhikari and Dahal, 2015; Bhattarai, 1987; Bhattarai and Maskey, 1988; Kannaiyan, 1982; Soil Science Division, 1992). Despite these benefits, there are however significant limitations to wide-scale and systematic use of BNF in Nepal. These include the relatively limited availability of appropriate inoculums at a commercial scale, in addition to constraints associated with their preservation and transport. Educational programs to increase farmers' awareness of the benefits of inoculants when pulses are rotated with cereals are also lacking. Lastly, yield responses to inoculants take time (Adhikari and Dahal, 2015); relative to the responses that farmers observe with synthetic fertilizers, methods to convincing farmers of their benefits remains a challenge that could be addressed through behavioral sciences research.

6.2.2 Climate variability and change

Research highlighted in this review suggest that Nepal's climate is changing, albeit with varying effects across locations (Bharati et al., 2016; Budhathoki et al., 2020; Lamichhane and Shakya, 2019; Pandey et al., 2019, 2020; Shrestha et al., 2020). Changes in temperatures, precipitation distribution, and seasons have affected crop yields negatively. These changes are also projected to affect food security in the long run (Bannayan et al., 2011; Hossain et al., 2018; Kukal and Irmak, 2018; Paudel, 2016a,b). Despite a reasonable number of studies on climate change, robust and detailed research related to the impact of climate change and variability on crop productivity and the economic consequences and desirability of options to adapt agriculture to climate change in Nepal remains somewhat limited.

Research summarized in this review indicates that western Nepal, and particularly the Terai, are experiencing increasing temperatures. In rice-wheat cropping systems in the Terai, the delayed planting of wheat following late rice transplanting or harvesting can push back the maturation of wheat into periods of the year during which high temperatures are common. This results in terminal heat stress, which can reduce wheat yields (Adhikari et al., 1999; Puri et al., 2015). A recent study based on crop-cut survey data collected more than 1600 farmers across the Terai also showed that longer-duration wheat varieties coupled with early sowing could enable the wheat crop to maximizing field duration while permitting maturation just before the period of the year when temperatures become dangerously high. This arguably increases the potential for photosynthetic energy conversion—resulting in a yield gain of around $0.5\,t\,ha^{-1}$ compared with short duration varieties sown late (CSISA, 2019). Early establishment of rice—potentially through DSR or use of pre-monsoon irrigation to prepare fields for transplanting—can also aid in earlier harvest of rice after the monsoon, thereby facilitating earlier wheat sowing (Acharya, 2017). In addition to these approaches, use of heat-stress tolerant cultivars (Reynolds et al., 2016), and supplementary irrigation can aid in overcoming environmental stresses in the dry winter season (Shrestha et al., 2013a). Where maize grown is either in the winter and spring seasons in Nepal, but in particular for latter, the crop can suffer from heat stress during anthesis and flowering (Pandey and Koirala, 2017). As with wheat, early sowing is therefore recommended.

Variability in precipitation patterns was also highlighted by this review, particularly in the western Terai, as was late monsoon onset and within monsoon season drought (DHM, 2017; Sapkota and Devkota, 2019). Along with the gradual loss of glacier ice reserves and reduced stream and river flow, these factors affect groundwater recharge in Nepal (Doll, 2002; Hasan et al., 2019; Nyakundi et al., 2015; Panda et al., 2019; Pandey et al., 2019, 2020). Potential avenues to adapt to these changes include linked climate and hydrological information services that explicitly integrate farmer participation in the development of demand-driven advisories (Krupnik et al., 2018; Lourenço et al., 2016). To this end, the purposeful integration of research and planning activities conducted by NARC and the DHM could be beneficial.

In particular, the development of high-resolution weather, sub-seasonal and seasonal forecasts, as well as drought monitoring and forecasting (Qamer et al., 2020), represent important research gaps with direct applicability to agricultural planning. During the monsoon when excess precipitation and stream and river flow can result in flooding, agricultural insurance has been proposed as an important adaptation mechanism (Greatrex et al., 2015; Ghimire et al., 2016a; Fisher et al., 2019), although low enrollment in insurance programs remains a problem (Timsina et al., 2018a), indicative of the need for reform and new approaches (Budhathoki et al., 2019). A last area of importance that remains significantly under researched and under invested in Nepal is the use of climate information services—particularly localized weather forecasts and associated crop management advisories—to aid farmers in overcoming heat stress. There is currently a lack of systematic research on this topic, although demand for climate information services is accelerating elsewhere in the region and globally (Lourenço et al., 2016).

To cope with water scarcity during land preparation and within season drought, numerous options have been proposed through research and policy, including the cultivation of less water demanding and potentially profitable crops (e.g., maize, groundnut) as an alternative to rice, community or private sector nursery management, improved water management at the field level, and better education and coordination of water users. Alternate wetting and drying in rice has also been proposed (Carrijo et al., 2017), but has not yet gained considerable levels of adoption. Civil interventions include restrictions on poorly planned road construction and the destruction of springs in the hills that can affect downstream hydrology (Paudel and Duex, 2017). In addition, adequate groundwater resources mapping and increased abstraction may be warranted within safe environmental limits. Current evidence indicates substantial underuse of groundwater in Nepal, particularly in the Terai (Department of Water Resources and Irrigation (Sugden, 2014; Shrestha et al., 2018; Urfels et al., 2020, 2021).

6.2.3 Maintaining ecosystem services and environmental quality

This review has highlighted literature that indicates the potential for environmental externalities and reduction of ecosystem services where cropping systems intensification is poorly planned and executed (Rasmussen et al., 2018). In particular and although often profitable, intensive vegetable cultivation and double-cropping of cereals and vegetables in Nepal can be associated with high rates of synthetic fertilizers and pesticides that can reduce water quality (Dahal et al., 2009; Raut et al. 2010, 2011). Intensified cereal cropping can also be associated with infestations of soil nematodes (Timsina and Connor, 2001). These studies demonstrate that unplanned cropping systems intensification can also be a threat to environmental sustainability. Options to overcome these challenges include deliberate agricultural crop intensification planning and policies to account for potential negative environmental externalities, increased emphasis on agroecological management tactics and strategies, soil solarization (Culman et al. 2006), and a range of soil management practices highlighted in Table 10. In addition, awareness and educational programs that highlight the importance of ecosystem services and environmental quality could be beneficial, with messages appropriately targeted at diverse audiences including farmers, extension officers, and policy makers.

6.3 Addressing institutional and socioeconomic constraints

The key institutional and social issues that affect the functioning of Nepal's farming systems identified in this review include the performance of the seed system, rural labor availability and the feminization of agriculture, the management of agricultural risk, water resources management, and extension systems (Table 11).

6.3.1 Seed production, replacement, circulation, and delivery systems

Among the challenges facing seed systems in Nepal, the limited and uneven application of seed sector policies, low seed replacement rates, poorly functioning seed production, supply, and delivery systems are concerns. In addition, aflatoxin and pests and disease affecting both seed and stored grain were identified. To address these issues, actions that could be taken by both public and private stakeholders include (a) full implementation of the National Seed Vision 2013–2025's goals to achieve 25% seed replacement rates for rice and wheat, and 33% for maize (Gauchan, 2019; SQCC, 2013). In line with these goals, (b) seed quality standards and options for fast-tracking of promising varieties for release were highlighted as priorities, (c) efforts to increase private sector capacity in terms of company, species, and varietal line diversification, in addition to improved product development and marketing, alongside (d) improvements in seed processing plants, storage, and seed dryers. In terms of research capacity, (e) programs to

Table 11 Summary of major institutional and socio-economic challenges and opportunities in Nepal's cereal-based farming systems.

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
Seed production, replacement, circulation and delivery systems	Limited application of seed sector policies	• Implement recommendations by the National Seed Vision 2013–2025's goals to achieve 25% and 25% and 33% seed replacement rates for wheat and maize, respectively • Increase private sector engagement in varietal development, registration and distribution	Gauchan (2015, 2019), IFPRI (2016), Joshi and Joshi (2020), SQCC (2013, 2018), Mishra et al. (2017)
	Low seed replacement rates, limitations in seed production, supply and delivery systems	• Assure that 'truthful labelling' systems identify source and labeled as opposed to second and third generation seed • Limit non-seed multiplication uses of foundation seed • Increase production of certified wheat and hybrid maize seeds • Improve private sector access to financial services • Develop and implement appropriate varietal information and seed tracking mechanisms	ADS (2015), CSISA (2017, 2019), Ghimire et al. (2004), Joshi and Joshi (2020), Mishra et al. (2017), Sapkota and Pokhrel (2010), Tiwari et al. (2009a), Witcombe et al. (2005)

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Table 11 Summary of major institutional and socio-economic challenges and opportunities in Nepal's cereal-based farming systems.—cont'd

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
		• Administer policies permitting fast-tracking for registration of promising new seed varieties • Maintain in-situ and ex-situ systems to conserve agricultural biodiversity in varietal composition while increasing seed replacement rates	
	Aflatoxin, pest and disease contamination	• Develop systems by which farmers can accurately measure seed and grain moisture • Mechanical and solar grain dryers • Use of moderate to high nutrient application levels to maize • Removal of maize grain from cobs before sun drying Use of afalatoxin tolerant maize germplasm • Use of hermetic storage for seed	Basnyat (2017), CSISA (2018), Devkota et al. (2018a), Gautam et al. (2008), Pokhrel (2016)
	Poor seed germination	• Hermetic storage • Seed priming	Devkota et al. (2018a), Harris et al. 2001, Farooq et al. (2006), Pandey and Koirala (2017)

Labor availability and farm management	Labour out-migration, labor shortages and costs, feminization of agriculture	• Alternative employment options • Agricultural entrepreneurship • Agricultural machinery service provision • Mechanisms to increase rural wage labor payments for women • Formal increases in recognition of women's leadership in agricultural decision making • Scale-appropriate farm mechanization options • Financial services to increase access to mechanization options • Agricultural services provision (affordable fee-for-services)	Adhikari and Hobley (2015), ADS (2015), Ba et al. (2019), Biggs et al. (2011), Bossavie and Denisova (2018), CSISA (2017, 2019, 2020), Gartaula et al. (2010), Gauchan and Shrestha (2017), Holmelin (2019), Justice and Biggs (2013), Mazvimavi and Twomlow (2009), Meemken and Bellemare (2019), Keil et al. (2016), Krupnik et al. (2013), Spangler and Christie (2020), Paudel et al. (2019a,b, 2020a,b,c), Shrestha (2013), Shiferaw et al. (2009), Thapa (2010), Tiwari et al. (2004), Van Loon et al. (2020)
Agricultural risk management	Loss and damage	• Streamline settlement claim systems by integrating farmers' institutions • Index-based insurance • Balance premium subsidy offsets with willingness to pay studies and refine policy support as needed	Fisher et al. (2019), Budhathoki et al. (2019), Greatrex et al. (2015), Ghimire et al. (2016a,b), Timsina et al. (2018a)

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Table 11 Summary of major institutional and socio-economic challenges and opportunities in Nepal's cereal-based farming systems.—cont'd

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
Water resources management	Inefficiencies in irrigation supply, poorly functioning irrigation schemes, high energy costs for pumping	• Increase private investment in small-scale groundwater irrigation systems, including well drilling and irrigation services provision • Integrate groundwater recharge provisioning with flood prevention efforts • Re-orient farmers towards use of smaller and more efficient pumps • Monitor and learn from the successes and challenges faced in solar irrigation system roll-outs • Improve drainage systems in surface water schemes to reduce waterlogging constraints	Bharati et al. (2016), DWRI (2019), Foster et al. (2019), Justice and Biggs (2020), Khan et al. (2014), Ministry of Energy, Water Resources and Irrigation (2018), Mukherji (2017), Muthuwatta et al. (2017), Ritzema et al. (2008), Shah et al. (2006), Sugden (2014), Urfels et al. (2020, 2021)
Extension systems	Restructuring of extension services, delinking of research and extension, federal restructuring	• Improve extension human resources through technical skills and communication training for field-level extension staff • Improve physical infrastructure and transportation services for extension systems • Examine possible efficiency gains from partial transition to private-sector led extension services • Develop and nurture links between extension systems, including agricultural knowledge centres, and research institutions such as NARC	Babu and Sah (2019), Thapa (2010), Yilmaz et al. (2020)

increase breeding—particularly of climate stress-tolerant varieties—and seed technology and business management could prove beneficial. Similarly, (f) digital tracking mechanisms to monitor the amount and quality of seed produced and marketed by companies are largely lacking, indicative of a practical and important research and agricultural development gap. Lastly, (g) financial services and support for seed company start-ups and to expand operations of existing companies were highlighted by IFPRI (2016), Mishra et al. (2017), and Gauchan (2015, 2019).

In response to these issues, the CIMMYT-led Cereal Systems Initiative for South Asia (CSISA), Nepal Seed and Fertilizer, and Heat Stress Tolerant Maize for Asia projects have worked closely with the National Agriculture Research Council (NARC), and private seed companies started to intervene in these areas. Research and development activities have focused on the introduction and validation of market-ready hybrids, product allocation, and licensing of best-adapted products, in addition to the provision of parental lines and initiation of local hybrid seed production. As a result, the involvement of Nepalese private seed companies in hybrid seed production and marketing is gradually increasing (Choudhary et al., 2020). Although quantities remain limited, these activities have assisted in developing skills and creating an enabling environment for emerging seed companies to expand their businesses, to increase self-reliance in the seed sector.

To address issues in seed quality and grain storage, systems by which farmers can accurately measure moisture and assess disease during post-harvest drying appear to be an important priority. The NARC for example has worked to verify and recommended low-cost solar dryers as important components of cereal-based farming systems (Basnyat, 2017). CSISA (2018) conducted preliminary evaluations of management techniques to reduce aflatoxin contamination. Collaborating with the Department of Food Technology and Quality Center, data collected by CSISA indicated that pre-harvest aflatoxin levels in maize could be reduced through balanced fertilizer management. With balanced and moderate N, P and K application (60:60:60), all maize samples had very low aflatoxin levels of less than 1 ppb. With higher levels of N application (120:60:60), 40% of observed maize grain samples had aflatoxin levels of 1–10 ppb and 60% of the samples had aflatoxin levels below 1 ppb. Post-harvest aflatoxin levels can also be dramatically reduced by removing maize kernels from the cob and sun drying the grain before storage.

Devkota et al. (2018a) evaluated different wheat seed storage options against farmers' typical storage methods in a mid-hill and a Terai district, respectively, to identify efficient and cost-effective storage options. After

6 months of storage, hermetic storage bags, which are airtight and smother pests as they inhale O_2 but respire CO_2 (Alemayehu et al., 2020; Tubbs et al., 2016), followed by plastic bags supplemented with Celphus, a common pesticide with Aluminum Phosphide as the active ingredient, were found more effective in maintaining optimum seed moisture. These approaches also reduced insect damage, improving germination in both the laboratory and in farmers' fields. The same technologies were linked to enhanced seedling vigor, and a reduction in costs compared to farmers' storage methods, which included reused fertilizer bags, polythene bags, household metal containers, and mud bins. Importantly, improved storage (and specifically hermetically sealed bags) and seed priming were also identified in this review as key management interventions to improve seed germination. These findings demonstrate that seed priming and super grain bags can improve seed quality and seed germination. Combined with economic analyses indicating their low cost and potential for improving profitability, these methods appear to be promising simple but useful advances for seed storage and preparation before planting in Nepal.

6.3.2 Labor availability and farm management

Rural out-migration was identified in this review as an important driver of farming systems change in Nepal, resulting in the progressive feminization of agriculture (Adhikari and Hobley, 2015; Bhandari et al., 2015; Gartaula et al., 2010). While this has impacted the functioning of agricultural systems, remittances sent by migrants are also an important source of income for household members who remain behind in rural areas (Maharjan et al., 2013b). Between 2013 and 2016, remittances, for example, constituted 27.7 to 32.1% of Nepal's gross domestic product (ILO, 2017). This situation presents challenges in terms of rural labor scarcity and costs, but also opportunities, as remittances can permit re-investment in rural communities, while the feminization of agriculture can serve to empower women to make improved farm management decisions (Gartaula et al., 2017; Spangler and Christie, 2020).

Options to address these issues that were identified in this review include the development of alternative employment options and agricultural entrepreneurship (CSISA, 2019; Keil et al., 2016; Paudel et al., 2019b; Van Loon et al., 2020), as well as the formal recognition of women's role in farm management (Adhikari and Hobley, 2015; Gartaula et al., 2010). Increased use of 'scale-appropriate' farm machinery (Krupnik et al., 2013; Van Loon et al., 2020), including mini-tillers, rotavators, multi-crop planters, power tiller operated seeders, zero-till drills, multi-crop reapers, combine harvesters, threshers, and grain dryers present opportunities for the mitigation of high labor costs and farm drudgery. These options can also provide employment opportunities where machinery owners offer land preparation, planting, intercultural management, irrigation, harvesting, and post-harvesting services to other farmers on an affordable fee-for-services basis. Small-scale agricultural machinery may also be more appropriate given current land fragmentation trends in the Terai, in addition to rugged terrain and need for light-weight and easily transportable or mobile equipment suitable for the hills. The implications of these technologies on women's empowerment is, however, only beginning to be adequately studied (cf. Paudel et al., 2020a,b,c), indicative of a significant research gap. Similarly, mechanisms to increase loans or finance for the purchase of machinery—either through the provision of subsidies or through bank and financial service provider mechanisms—appear to be an important but under-researched pre-requisite for increased use of scale-appropriate farm machinery.

6.3.3 Addressing agricultural risk management

In this review, climate change, climate variability, and extreme weather events were highlighted as important challenges to Nepal's farming systems—particularly those managed by smallholders. Although the Government of Nepal has engaged rural communities by offering a 75% subsidy on insurance premiums to de-risk investment in agricultural insurance, adoption rates remain very low, especially in comparison to neighboring countries (Ghimire et al., 2016a). In addition to a lack of awareness of insurance options among farmers, constraints to crop insurance include lengthy claim settlement procedures (Ghimire et al., 2016b). Budhathoki et al. (2019) therefore argued that additional research is needed to identify avenues for reform and improvement of existing insurance schemes. Among these, this review highlighted the need for research into the feasibility of index-based insurance in comparison to indemnity insurance, and revisions to subsidy programs that account for farmers' willingness to pay for premiums, alongside research into how to popularize extension messaging on the potential benefits of insurance to Nepal's most at-risk farmers.

6.3.4 Agricultural water management

Improvements in the management of surface and groundwater to foster agricultural productivity were identified as key themes in this review. Several challenges for water distribution through canal irrigation schemes, high energy costs for groundwater pumping, and lack of coordination and education among water users appear to be important constraints (DWRI, 2019; Urfels et al., 2020, 2021). Research needs to address these problems identified include (a) methods and systems to adequately monitor aquifers and their seasonal recharge (Sugden, 2014; Urfels et al., 2020, 2021), in addition to (b) the integration of recharge with flood mitigation and drainage systems (Ritzema et al., 2008; Paudel et al., 2020a,b,c), and (c) increased private investment in small-scale groundwater irrigation (Shah et al., 2006; Urfels et al., 2020, 2021). These are in addition to (d) increased monitoring and adaptive management of solar irrigation systems, (e) and better linking water users to markets, knowledge providers, input supply chains, and service providers. This includes the recent roll-out of 1600 solar pump instillations aimed to be completed before 2030 (Mukherji et al., 2017; MoEWRI, 2018).

6.3.5 Extension system reform

Since the adoption of the new constitution in 2015, Nepal has been in the process of governmental restructuring, and the progressive decentralization of administrative authority to the local level, including agricultural extension systems. Extension is now administered primarily at the local level, with a consequent decoupling of extension from regular communication and joint work planning, decision making, and agenda setting with NARC and associated research organizations. To address these issues, this review highlighted the need for increased human resources and improved technical capacity and infrastructure (Babu and Sah, 2019; Kyle and Resnick, 2019). This review also highlighted important research gaps, namely the lack of emphasis on how to increase feedback and cooperative learning among research and extension agencies, in addition to studies evaluating if and how the private sector could provide some level of formal extension support to farmers.

6.4 Agronomic constraints and research gaps

Among the agronomic constraints and research gaps identified in this review, yield gaps and the intersection of soil management with tillage and crop establishment, were identified. These are in addition a lack of research on finger millet and needed improvements in irrigation and integrated pest and disease management. Lastly, research on agroforestry options to arrest soil erosion and the low productivity of integrated crop-livestock-tree systems, while having a foundational base of some literature, could be enhanced. These topics are summarized in Table 12 and briefly discussed below.

Table 12 Summary of major agronomic challenges and opportunities in Nepal's cereal-based farming systems.

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
Yield potential and yield gaps	Cereals import dependency, low yield potential for cereals (exempting wheat), large gaps between research station and farmers' yields, large gaps in yield between top and average performing farmers, missed opportunities to increase cropping intensity	• Appropriate use of high-yielding, stress-tolerant and hybrid cultivars • Sowing within optimal date ranges to avoid terminal heat stress • Appropriate fertilization rates to meet yield targets • Strategic use of short- and medium-duration cultivars in multi-crop rotations to achieve high 'systems' yield • Precision nutrient and irrigation management, including decision support tools • Strategic research on millet yield enhancement in the hills	Adhikari (2012), Amgain and Timsina (2004), Bhatta et al. (2020), CIMMYT-IFAD (2013), CSISA (2019), Devkota et al. (2015, 2016, 2018b), Timsina et al. (2010, 2011)
Soil management, tillage, and crop establishment	Erosion and nutrient losses, declining soil fertility and soil structure, greenhouse gas emissions	• Rational implementation of the principles of conservation agriculture • Land terracing • Soil ridging • Straw mulching • Directly sown rice, with potential sequencing of early sown wheat	Acharya (2017), Atreya et al. (2005, 2008), Devkota et al. (2019), Dixon et al. (2019, 2020), Gathala et al. (2020), Ghimire et al. (2011), Islam et al. (2019), Karki et al. (2014a,b), Laborde and McDonald (2019), McDonald et al. (2006a,b), Partap and Watson (1994), Schreier et al. (2001), Sherchand and

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Table 12 Summary of major agronomic challenges and opportunities in Nepal's cereal-based farming systems.—cont'd

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
		• Behavioral science research to study patterns in farmers' decision making and technology adaptation, adoption, and abandonment patterns • Educational programs to overcome the perceptual hurdles that may limit farmers' use of CA, including raising awareness of the importance of environmental in addition to profitability outcomes in the hills	Gurung (1995), Tiwari et al. (2008b, 2009b,c)
	Cultural management to avoid terminal heat stress in the Terai	• Early sowing of wheat • Early planting of long-duration wheat varieties to maximize photosynthetic capture while avoiding terminal heat stress	Adhikari et al. (1999), CSISA (2017, 2019), Pandey and Koirala (2017), Puri et al. (2015)
	Nitrate and soil moisture losses during the dry-wet transition period during spring in the Terai (after wheat or maize, and before rice planting)	• Early establishment of rice • Alternative late establishment of rice using high-yield potential, long duration cultivars • Careful incorporation of residues to temporarily immobilize N and limit losses • Establishment of catch crops to conserve nitrate and soil water and reduce their losses	Becker et al. (2007), Pandey and Becker (2003), Shrestha et al. (2011), Timsina and Connor (2001), Timsina et al. (2010)

	Inadequate knowledge on fertilizer and nutrient management, limited use of organic matter additions. Generally low and unbalanced fertilizer use, declining long-term rice and wheat yields, informal fertilizer trade and lack of quality control	• Use of digital soil maps to aid crop nutrient recommendations • Development of the compound fertilizer industry and products • Application of appropriate, balanced fertilizer rates, including even spreading of fertilizers • Integrated soil fertility management favoring combinations of organic matter with fertilizer addition • Diversify rotations away from cereal–cereal systems • Increase K rates in rice • Improve nutrient cycling through livestock integration	CSISA (2020), Devkota et al. (2015, 2016), Desbiez et al. (2004), Gami et al. (2001), Hoyum (2012), NSAF (2017), Ladha et al. (2003), Park et al. (2018), Pandit and Balla (2006), Paudel and Thapa (2001), Pandey et al. (2018b), Pilbeam et al. (2000), Takeshima (2019), Pilbeam et al. (1999, 2002), Regmi et al. (2002a,b), Takeshima et al. (2016), Timsina and Connor (2001), Tripathi and Jones (2010), Westarp et al. (2004)
Revitalizing millet production in hills	Low yields of millets, high manual labor demand for transplanting, weeding, harvesting, and threshing	• Development of systems for direct seeding and transplanting of millet • Evaluation of integrated weed management tactics appropriate for millet • Small harvesters and threshers • Millet varietal development • Improvements in small-scale brewing and distilling and market development	Adhikari (2012), Dayakar Rao et al. (2017)

Continued

Table 12 Summary of major agronomic challenges and opportunities in Nepal's cereal-based farming systems.—cont'd

Challenges	Key problems and constraints	Potential agricultural development interventions and research needs	Background studies and evidence for opportunities
Improved irrigation management	Delayed monsoon onset and sequential delays in crop establishment, within monsoon season drought	• Improved weather, sub-seasonal, and seasonal precipitation forecasts with associated irrigation advisories • Early and supplemental irrigation • Directly sown rice • Shorter duration rice varieties • Alternate wetting and drying and avoidance of soil cracking in rice • Matching dry season irrigation rates and volumes with fertilizer rates and timing • Improved irrigation infrastructure	Singh et al. (2019), Carrijo et al. (2017), McDonald et al. (2006a,b), Devkota et al. (2019), Paudel et al. (2020c), Newport (2020), Shah et al. (2020), Shrestha et al. (2013a,b), Urfels et al. (2020, 2021)
Pests, diseases and weeds	Wheat leaf and stem rust, Turcicum leaf blight, Gray leaf spot, Fall Armyworm, *Parthenium hysterophorus* L., *Phalaris minor*	• Climate monitoring and disease early warning systems • Disease resistant and tolerant varieties • Crop rotation to reduce pest and disease pressure • Biological control (*Telenomus* spp., *Trichogramma chilotraeae*, and *Brachymeria ovata* for Fall Armyworm) • Zero-tillage to control *P. minor*	Adhikari (2017), Bhusal and Bhattarai (2019), Bhusal and Chapagain (2020), Chauhan et al. (2001), Culman et al. (2006), Gc et al. (2019), Lamsal and Khadka (2019), Manandhar et al. (2011), Malik et al. (2000), Paudyal et al. (2001), Ranjit et al. (2009), Regmi et al. (2002b), Wise (2010), Timsina and Connor (2001)
Agroforestry systems	Soil erosion, low productivity of crop-livestock-tree based agroforestry systems	• Contour plantings and hedgerows to stabilize slopes • Nitrogen fixing tree species • Multi-purpose agroforestry species integration with livestock	Garrity (2004), Mango and Hebinck (2016), Partap and Watson (1994), Schwab et al. (2015)

6.4.1 Yield gaps

Our review of available data indicates that when considered at a national level, the yield potential of rice and maize in Nepal appear to be less than what is normally expected in South Asia. Wheat however appears to be an exception (Devkota et al., 2015, 2016, 2018b). This is likely a consequence of the dramatic range of elevation and different agroecological zones observed in Nepal (MoALD, 2018). Similarly, average yields obtained by farmers in Nepal tend to be well below estimates of attainable yield. These factors render Nepal largely dependent on the import of cereals to meet national demand (FAOSTAT, 2019). Key approaches identified that can address these gaps include (a) appropriate use of hybrid varieties (Devkota et al., 2016), particularly for maize farmers selling their produce to emerging poultry feed markets (Timsina et al., 2016), (b) sowing within optimal date ranges to avoid heat stress, particularly for wheat and maize (Pandey and Koirala, 2017; Puri et al., 2015; Reynolds et al., 2016), as well as for the rice crop that proceeds these cereals in rotation, (c) more appropriate application timing and improvements in SOM reserves to achieve increased efficiencies in nutrient recovery from applied fertilizers, alongside site-specific and precision application of balanced fertilizers (Devkota et al., 2015, 2016, 2018b; Bhatta et al., 2020), a (d) tactical use of short- and medium-duration cultivars in multi-crop rotations to achieve high 'systems' yield (Timsina et al., 2010, 2011).

Our review indicates there is a substantial body of knowledge on methods that can be applied to reduce yield gaps, particularly in irrigated cropping systems in the Terai. There is however significantly less research on these topics and the combinations of best management practices that can aid in reducing gaps in Nepal's hill and mountain environments. Similarly, the literature insufficiently characterizes the perceived risks vs. potential benefits of improved and intensive crop management among farmers. In summary, biophysical and process-based research has identified a suite of tools and techniques that can be used to reduce yield gaps, but much less is known about best approaches for successful extension, or methods to overcome the very real adoption hurdles that smallholder farmers face.

6.4.2 Soil management and tillage and crop establishment

There is a wide variety of literature available that pertains to this topic in Nepal. Some key themes that differentiate research include studies aimed at reducing erosion, nutrient losses or declining soil fertility (Atreya et al., 2005; Ghimire et al., 2011; McDonald et al., 2006a,b; Partap and

Watson, 1994; Schreier et al., 2001; Tiwari et al., 2009c), and the mitigation of greenhouse gas emissions (Gathala et al., 2020; Laborde and McDonald, 2019). The latter is however comparatively understudied in Nepal. Adaptations in the timing and methods that farmers use for tillage and crop establishment have also been linked to efforts to escape from terminal heat stress, particularly in wheat (Adhikari et al., 1999; CSISA, 2017, 2019; Pandey and Koirala, 2017; Puri et al., 2015). The timing of crop establishment and method used to manage nitrate and soil moisture losses in the fallow period before the monsoon and in spring planted maize have also received research attention (Becker et al., 2007; Pandey and Becker, 2003; Timsina and Connor, 2001; Timsina et al., 2010; Shrestha et al., 2011), as have problems with soil fertility (Tripathi, 1999a,b; Bajracharya and Sherchand, 2009; Dawadi and Thapa, 2015; Huang et al., 2015). Soil information systems (Pandey et al., 2018a), and the poor quality and lack of balanced fertilizers used by many farmers in Nepal were also identified in this review (Amgain and Timsina, 2004; NSAF, 2019; Timsina et al., 1997).

Approaches to mitigate erosion, nutrient losses, declining soil fertility and structure highlighted in this review include the rational integration and use of CA techniques (cf. Dixon et al., 2020), well maintained land terraces (Shrestha, 1997; Tiwari et al., 2009b), and reduced and ridge-till systems, in addition to the maintenance of soil cover through mulching or multiple cropping (Brown and Shrestha, 2000; Partap and Watson, 1994; Tiwari et al., 2008b). Considering cultural management to overcome heat stress, an expansion in the use of validated as well as new methods to assure early wheat sowing was highlighted as a key need. Research on how to most efficiently establish wheat under on-farm conditions is however limited in Nepal relative to neighboring India. Several options that address this issue from a cropping systems standpoint are summarized in Section 6.2.2.

As rice-wheat and rice-maize systems in the Terai are largely dependent on indigenous soil supply of nutrients (Timsina and Connor, 2001; Timsina et al., 2010), tactics contributing to an overall strategy to build soil fertility and maintain nutrient reserves are crucial. In these cropping sequences, there is typically a 2–3 months fallow period after harvest of wheat and before the planting of summer monsoon rice. Management interventions during this dry-to-wet transition period should aim to avoid of losses of native soil N. To reduce such losses, this period could either be shortened by planting rice earlier, or it could be extended by planting rice later. The former option allows the establishment of a long-duration variety with high yield potential, while the later permits the growing of a short-duration catch crop such as mungbean or spring maize to capture N and minimize their losses. Extending this interim period would require short-duration rice genotypes, low thermal requirements for development, and cold tolerance during the reproductive stage to avoid cold sterility related yield losses (Shrestha et al., 2011).

Becker et al. (2007) observed that incorporation of wheat straw and/or cultivation of a catch crop during this period significantly reduced the buildup of soil nitrate and subsequent N loss in low (Chitwan, 250 m) but not at high altitude (Lumle, 1740 m) locations. At both sites, cumulative rice-wheat system yields were higher when straw was incorporated, or fallows were managed with a catch crop. Yet irrespective of the sites and the land use options during this period, N balances remained largely negative, ranging from -37 to $-84\,\text{kg N ha}^{-1}$. This indicates that while some benefits can be obtained through these practices, completely arresting soil N losses is likely to be challenging. Economic crops can also be integrated to reduce fallows and manage soil nutrient reserves; mungbean, for example can be sequenced after wheat and before rice in the Terai (CSISA, 2020), although rigorous evaluation of the wide-scale applicability of this system remains lacking. These issues highlight that research on how to minimize N losses from Nepal's diverse farming systems is still needed, with efforts aimed at developing practical and actionable solutions for farmers in both the Terai and the hills.

Finally, our review highlighted the need for improved soil intelligence systems, particularly high-resolution and accurate soil maps that can be used to aid farmers, extension advisers, and agricultural policy makers in guiding future soil fertility investments. In addition to initial efforts to develop such systems (Pandey et al., 2018a), the NARC is currently working with support from the Nepal Seed and Fertilizer (NSAF) project to prepare a digital soil map of Nepal to identify and quantify soil texture, soil pH, SOM, total N, available P and K, and micronutrients including boron and zinc. Maps are being prepared using soil information from 23,273 soils samples collected from 57 out Nepal's 77 districts covering seven provinces and stack of 168 remote sensing-based soil covariates. Soil data were collected from different government projects including National Land Use Project (NLUP), Irrigation and Water Resource Management Project and from the Central Agriculture Laboratory (previously the Soil Management Directorate). Preliminary outputs of the map are to be uploaded on an interactive portal.

6.4.3 Revitalizing millet research in the hills

Grown primarily in the hills, finger millet is Nepal's fourth most widely grown cereal (FAOSTAT, 2019), although it has become a largely forgotten crop in terms of research and technical improvements. This is arguably unfortunate, as finger millet is comparatively rich in nutritional content—with high concentrations of calcium—and is known for its long-release during digestibility, rendering it a healthy food for lactating and pregnant women, as well as and diabetics (Dayakar Rao et al., 2017). In addition to direct consumption, millet is also commonly used to produce traditional alcohols in the Nepalese hills and mountains.

The cultivation of millet, which is often relayed with maize, is relatively labor intensive given that human energy is the primary source of farm power used for transplanting, weeding, harvesting, and threshing. Our review of the literature indicates that research is needed to develop innovations aimed at direct seeding of millet, millet transplanters, evaluation of integrated weed management tactics, and small harvesters and threshers that could assist in addressing some of these constraints. Suitable relay and/or intercropping management practices for millet relayed with maize represent research needs. Use of green and brown manures from *Sesbania* spp. or sanai (*Crotalaria juncea*), or mixed planting with legumes such as black gram may also be beneficial and could be researched as mechanisms to suppress weeds and enrich soil fertility (Khadka et al., 2016a,b). In addition, more fundamental research to develop improved short-duration varieties is needed. Value addition by mixing millet with other grains during food processing could assist in stimulating millet production by incentivizing farmers with markets and food processors with more diverse options for milling. Improvements in small-scale brewing and distilling and market development are also recommended.

6.4.4 Improvements in within-field irrigation management

Climate variability—particularly delayed monsoon onset and within monsoon season drought (Singh et al., 2019; CSISA, 2019; Urfels et al., 2020, 2021)—were highlighted in this review as important challenges that require improvements in irrigation management, particularly for rice. Several options for the integration of climate information services with agricultural advisories, which could be strongly applied to irrigation management, are discussed in Section 6.2.2. In addition, this review has discussed the role of early and supplemental irrigation (Urfels et al., 2020, 2021), alternate wetting and drying (Carrijo et al., 2017), and the need to avoid soil cracking, which is associated with reduced efficiency of supplementary irrigation in rice (Tuong et al., 1996; Zeng et al., 2020). Based on this literature and our review of environmental, institutional and socioeconomic issues challenging Nepal's cereal-based farming systems, we suggest that future research and policy on the agronomic aspects of supplementary irrigation should focus on (a) finding cost-effective irrigation scheduling strategies that are sustainable and work for different types of farmers and technologies, (b) accounting for local district-level variation in environmental factors, and (c) focus on moments of critical water needs such as crop establishment and flowering.

6.4.5 Integrated pest, disease, and weed management

Cereals account for more than 65% of the application of fungicides, herbicides and insecticides in Nepal (Adhikari, 2017). New and invasive species that challenge cereal farming systems include Fall Armyworm and *Parthenium hysterophorus*. Diseases are an ongoing challenge. Our review of highlighted consistent problems with *Helminthosporium* spp. (Regmi et al., 2002b), and leaf and stripe rusts in wheat (CIMMYT 2020). Turcicum leaf blight is now a key problem in more intensive maize systems in the cooler mid-hills (Paudyal et al., 2001). Gray leaf spot is a recent and problematic disease that particularly affects maize when grown in continuous monoculture (Manandhar et al., 2011).

Despite these challenges, research has also increasingly documented the role of conservation biological control in cereals—with much emphasis given to rice—including both arthropod and vertebrate predators (Khatiwada et al., 2017). Options for augmentative biological control of Fall Armyworm that are likely to hold promise in Nepal include *Telenomus* spp. and *Trichogramma chilotraeae*, both egg parasitoids (Bhusal and Chapagain, 2020). Diseases can be at least partially managed though tactical crop rotations (cf. Wise, 2010) while a range of options for integrated weed management are also available. Our review however highlighted several important research gaps, including a conspicuous lack of research on the potential role of weed competitive cultivars and insufficient attention on how climate information services can be combined with disease and pest modeling to provide early warnings and advisories for farmers on when and where to protect their crops. In addition, studies on the viability of integrated pest management techniques in comparison to the economic, human health, and environmental consequences of chemical pest management strategies deserve future research attention.

6.4.6 Agroforestry systems

The integration of trees with cereal and livestock systems is common in Nepal, particularly in the hills (Dhakal and Rai, 2020; Partap and Watson, 1994). Agroforestry may be defined as a farming system in which perennial trees are integrated into the production of annual cereal, vegetable, fodder and livestock systems (Sanchez, 1995). The interspersion of trees and crops in well-designed agroforestry systems is however far from haphazard; rather, emphasis is placed on the geometric planting of trees—often on contours or as hedgerows and fences, in addition to as intercrops—in the right proportions with crops so that tree canopies and crop and tree residues can protect the soil with coverage to limit nutrient losses, while also providing nutrients to build and maintain soil fertility for crop needs. These are in addition to the provision of green fodder for livestock (Garrity, 2004; Mango and Hebinck, 2016). Our review touched upon the importance of agroforestry systems for the control of soil erosion in Nepal's hills (Schwab et al., 2015), particularly through contour plantings and the integration of N fixing tree species (Partap and Watson, 1994).

Schwab et al. (2015) demonstrated that a fully developed agroforestry system could improve soil quality and soil fertility over time, and were associated with increased pH, aluminum content, base saturation, electrical conductivity, SOM and total N content, and cation exchange capacity compared to conventional mono-cropping systems the mid-hills of Nepal. These observations were obtained from fully mature (20+ yr old) agroforestry systems with a multitude of nitrogen-fixing trees, as well as Apricot (*Prunus* spp.) and Nepali Alder (*Alnus nepalensis*). These species were in addition to shrub species and a variety of crops, including legumes. Most of the perennial trees were grown on terrace risers and some on fields, while annual crops were grown on terraces. Livestock species were raised for manures and no synthetic fertilizers used. Another regenerative option for farming in high-slope environments is the Sloping Agricultural Land Technology (SALT) introduced by the International Centre for Integrated Mountain Development, or ICIMOD (Partap and Watson, 1994). SALT involves the dense contour planting of fast-growing nitrogen fixing hedgerow species to trap sediment and limit runoff.

Studies on agroforestry systems and their longer-term interactions with the various hill cropping systems are however meager in Nepal, and therefore are an important area for future research. Existing and new potential agroforestry systems require careful evaluation for indicators including land management ease, gendered labor demands and economic efficiency, addition to contribution to land restoration and food productivity across a range of soil types typical to the country's diverse agroecological regions. Lastly, research on how to minimize labor demand in agroforestry systems is needed in light of rural-out migration and the feminization of agriculture in Nepal.

7. Conclusions

This review has highlighted how the economic, environmental, and social sustainability of Nepal's major cereal-based farming systems in the Himalayan landscapes of South Asia is complicated by the interlinked effects of land degradation, and farmland fragmentation and abandonment, in addition to soil fertility, climate variability and change, and water resources management challenges. These are coupled to institutional and socio-economic constraints that affect seed systems, rural labor availability, agricultural risk management, and extension systems. Key agronomic challenges identified include efforts to close yield gaps through improved soil fertility, tillage and crop establishment, irrigation, and integrated pest management. Available literature indicates that significant scope exists for improving sustainability and realizing food and nutritional self-sufficiencies through tactical interventions in these farming systems.

In the Terai, options that require further research include, but are not limited to, methods to improve soil organic matter and nutrient reserves and increase the efficiency of nutrient recovery, while strategically using groundwater reserves to harness the benefits of reliable irrigation supply. Large knowledge gaps on the spatial distribution of soil nutrients and a lack of options for integrated soil fertility management—including the use of compound and balanced fertilizers—represent important research needs. Due to the progressive agricultural feminization through rural out-migration, profitable, accessible, and gender-responsive labor-saving farm machinery options represent another topic that deserves both research and agricultural development attention. Improved access to advisory services—both from traditional extension and through climate information services—could also help to mitigate production risks, as could improvements in the functioning of crop insurance schemes. Similarly, redoubled efforts to confront the challenges associated with climate change, and particularly with heat stress and precipitation variability, are needed.

Key issues in the hills that were identified in this review include land abandonment, soil erosion, and labor-outmigration, among others. Our review highlighted options for improvements in land terracing and agroforestry to address the former, while scale-appropriate farm machinery appears to be of importance even in remote hill environments. Despite the urgency of these topics, they lack significant bodies of recent research that could be addressed through future studies. Similarly, we identified improvements in millet—which is Nepal's fourth most widely grown cereal that is cultivated mainly in the hills—as significantly under-researched.

Nepal's contrasting environments and complex challenges are likely to require integrated solutions and systems thinking. In addition to biophysical themes, this review has highlighted the importance of linking agronomic studies in an interdisciplinary framework that incorporates research on institutional functioning, policy, socioeconomics, and behavioral sciences, among others. These themes—which are important complements to actionable agronomic research—are however unfortunately underinvested in, and consequently understudied, particularly in Nepal's national research systems. Efforts that approach research through multi-stakeholder engagements and that prioritize and account for input from extension systems, universities, the private sector, civil society, and donor communities and international development organizations will be needed. In response and conclusion, and to be practical and impactful, future agronomic research in Nepal, and indeed in much of South Asia, could benefit from the strategic integration of and communication with other disciplines.

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