



Intercropping of maize, millet, mustard, wheat and ginger increased land productivity and potential economic returns for smallholder terrace farmers in Nepal



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ABSTRACT

Low nitrogen inputs, low crop yield, and low land productivity are major challenges associated with cereal-based sole cropping systems in Nepal. Crop intensification and diversification by introducing legumes as intercrops could help alleviate these challenges. With the presence of diverse crops and cropping systems, particularly in hilly topographies, a range of intercrop options is required. We compared 10 intercrop combinations to native sole cropping systems in the mid-hills of Nepal for two cropping seasons (2015–2017) to identify the most productive and economic intercrop combinations for smallholder terrace agriculture. In the spring-summer season (i.e., mid-March to mid-July), cowpea (var. Makaibodi and Suryabodi) and bean were intercropped with maize in 1:1 rows, whereas soybean, blackgram, and horsegram were broadcast with millet (30:70 ratios) during the rainy-autumn season (i.e., mid-July to mid-November). Pea and lentil were used as pre-winter/winter intercrops (i.e., mid-November to mid-March) in mustard (30:70 ratios), while wheat was planted with pea. Ginger was planted with maize in 1:1 rows during the spring-summer season in which the maize rows were replaced by soybean and lentil during the rainy-autumn and pre-winter/winter season, respectively. Plots were analyzed for yields of individual crops as well as other agronomic indicators including land equivalent ratio (LER), total land output (TLO), harvest index (HI), and potential economic return.

Maize + cowpea var. Makaibodi appeared to be the most productive and economic intercrop combination for the spring-summer season (LER = 1.58 and TLO = 4.26 t ha⁻¹, 21% higher than the maize sole crop with an increase in potential economic return by 67%) whereas millet + soybean appeared to be the best combination for the rainy-autumn season (LER = 1.40 and TLO = 2.21 t ha⁻¹, 26% higher than the millet sole crop with a 288% increase in potential income). For the pre-winter/winter season, wheat + pea and mustard + pea combinations appeared to be productive (wheat + pea: LER = 1.31 and TLO = 2.90 t ha⁻¹ i.e., 16% higher than sole wheat with a 54% increase in potential income; mustard + pea: LER = 1.36 and TLO = 2.14 t ha⁻¹ i.e., 30% higher than sole mustard with a 15% increase in potential income). The year round intercrop system (i.e., ginger + maize-soybean) displayed a LER value of 2.45 with increased TLO (21.8 t ha⁻¹ i.e., 2% higher compared to sole ginger) which increased potential economic return by 6%. We conclude that legume intercropping was a robust option across seasons and locations confirming that it could be a promising ecological practice for intensification of cereal-based sole cropping systems on smallholder terraces. Also, it is important to note that soybean and pea provided higher potential net income to farmers as sole crops compared to when they were grown with millet and wheat as intercrops, respectively. It is important that we promote these options to smallholder farmers and disseminate the advantages of legume integration on land productivity, soil fertility management, and income.

Abbreviations: HI, harvest index; LER, land equivalent ratios; LI-BIRD, Local Initiatives for Biodiversity, Research and Development (a Nepalese NGO); masl, meters above sea level; ppm, parts per million; SAKNepal, sustainable agriculture kits for Nepal (a Canadian-funded international development project); SOM, soil organic matter; TLO, total land output

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1. Introduction

The production challenges attributed to cereal-based sole cropping systems on terraces are related primarily to low yield and low land productivity often arising from inappropriate agronomic management strategies. Farming in these regions mainly involves low external input rainfed farming to maintain livelihoods that decrease soil organic matter while increasing soil erosion, loss of soil fertility, and acidification (Chapagain and Raizada, 2017a; Wymann von Dach et al., 2013; Chapagain and Gurung, 2010; Riley et al., 1990). In addition, farming in remote terraces involves cultivation on poor quality land, poor access to agricultural inputs and services, lack of mechanization, labour shortages, poverty, and illiteracy (Chapagain and Raizada, 2017a).

Improving land productivity is essential to meeting the increasing demands of food and forage in hillside and mountain communities in Nepal where the majority of farmers are subsistence, with an average land holding of 0.68 ha (CBS, 2011). These regions are characterized by highly variable land use systems (e.g., rainfed *Bari* system in upland and the *Khet* system in irrigated lowland) (Regmi and Zoenisch, 2004). Farmers in both of these regions grow cereals as their staple diet. They typically harvest 2–3 crops in a year in sequence, and their choice of crops and cropping system is determined by multiple drivers such as climate, soil type(s), topography, household needs, availability of agricultural inputs (e.g. seeds, fertilizers, etc.), labour, and local market opportunities (Chapagain and Raizada, 2017a; Riley et al., 1990).

The major crops grown in the rainfed *Bari* system include maize (*Zea mays* L.), finger millet (*Eleusine coracana* L.), wheat (*Triticum aestivum* L.), and/or mustard (*Brassica nigra* L.). These are grown as sole crops during the rainy-autumn (i.e., mid-July to mid-November), spring-summer (i.e., mid-March to mid-July), and pre-winter/winter seasons (i.e., mid-November to mid-March), respectively, while rice (*Oryza sativa* L.) is mainly grown in the *Khet* system. Legumes, such as cowpea (*Vigna unguiculata* L. Walp.), common bean (*Phaseolus vulgaris* L.), soybean (*Glycine max* L. Merr.), horsegram (*Macrotyloma uniflorum* Lam. Verdc.), blackgram (*Vigna mungo* L. Hepper), field pea (*Pisum sativum* L.), and lentil (*Lens culinaris* Medik.) are also grown in the upland *Bari* system depending on the season (Chapagain and Raizada, 2017a; Chapagain and Gurung, 2010). Ginger (*Zingiber officinale* Roscoe), which takes ~10 months to mature, is also a popular cash/spice crop in the *Bari* system.

The variable and vulnerable nature of the terrace cropping system can be addressed by providing farmers with a menu of diverse options that are compatible with the growing season and location, including intercropping (Chapagain and Raizada, 2017a, b). Intercropping is when two or more crops are planted together on the same land (Ofori and Stern, 1987). Intercropping can be in rows, mixed, relayed or in strips depending on the method and time of planting. Row intercropping is when two or more crops are planted together in rows while mixed intercropping refers to broadcasting (Chapagain, 2016, 2014; Chapagain and Riseman, 2015, 2014a). Typically, intercrop components are from different species or families, with one crop of primary importance (e.g., food production) and the other crop primarily providing additional benefits (e.g., N₂ fixation from legume species). An effective intercrop combination is one that provides greater total yield on a piece of land and uses resources more efficiently than would otherwise if each crop was grown as a monoculture (Inal et al., 2007).

Intercropping is considered as a promising agronomic option for terrace intensification that enhances productivity and environmental sustainability in upland (i.e., rainfed *Bari* system) as well as irrigated lowland (i.e., *Khet* system where legumes can be relayed with rice) regions (Chapagain and Raizada, 2017a). A few studies in the mid-hills of Nepal (e.g., Prasad and Brook, 2005; Subedi, 1997) have demonstrated that intercrops offer higher efficiency and economic returns than sole crops, but to enable wider adoption, farmers in this system should have a diversity of intercrop options that have been scientifically

validated. In Nepal, some legumes such as cowpea, beans, and pea are grown as intercrops with maize, wheat or mustard; however, the productivity and potential economic return of each intercrop are not based or backed up by systematic on-farm research (Chapagain and Raizada, 2017a).

The current study evaluates the opportunities of using legumes as intercrops into maize, millet, wheat, mustard, and ginger to provide farmers in the mid-hills of Nepal with a menu of the most productive and economically profitable intercrop combination(s) for different growing seasons and household needs.

2. Materials and methods

2.1. Study site, climate and soil description

This study was conducted in two mid-hill districts of Nepal namely, Dhading and Kaski, for two cropping seasons from 2015 to 2017. The experimental sites in Dhading were located at 27° 78' 84" N and 84° 70' 02" E, at an altitude of 700–1300 m above sea level (masl) while the sites in Kaski were situated at 28° 20' 25" N and 84° 11' 71" E, at an altitude of 1100 masl. Research was conducted on farmers' fields under natural climatic conditions.

Climatic data for the experiment were collected from a regional weather station at the research site (Fig. 1). Average day-time temperature over the three cropping seasons (April–July, August–November and December–March) were 27.8 °C, 23.5 °C, and 18.3 °C in Dhading and 24.4 °C, 21.9 °C, and 16.3 °C in Kaski with the warmest days in May through August at both sites. Both Dhading and Kaski received more rainfall (annual total of 2660 mm and 3459 mm, respectively) in 2016 in comparison with 2015, with season 1 (i.e., April–July) receiving the most (1408 mm and 1758 mm, respectively). Both sites received the least rainfall in pre-winter/winter (October through February), with no rains in November–December (Fig. 1).

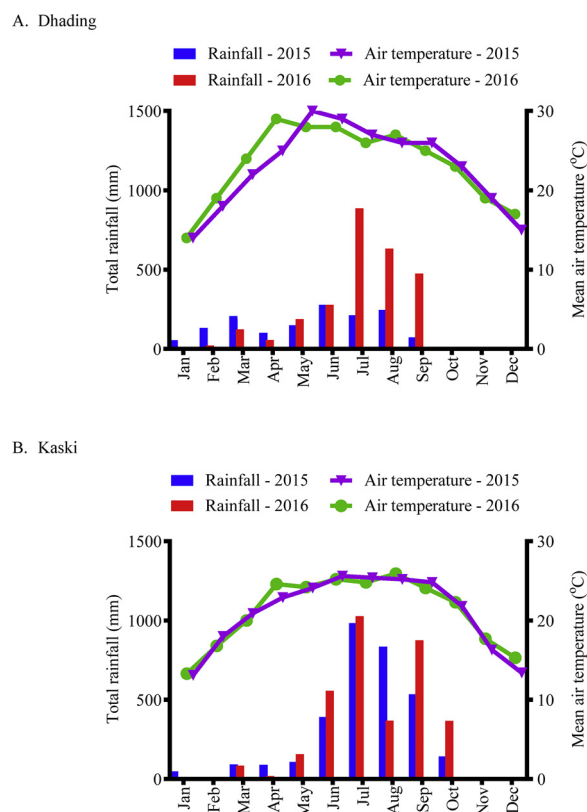


Fig. 1. Climatic data (air temperature and rainfall) collected for (A) Dhading and (B) Kaski districts in 2015 and 2016.

Table 1
Baseline and post two-season soil fertility measurements^a from non-legume sole crop and intercrop plots in Dhading and Kaski districts of Nepal.

Fertility Indicator	Dhading			Kaski			Location Average		
	Baseline	Post 2-Seasons		Baseline	Post 2-Seasons		Baseline	Post 2-Seasons	
		Sole	Intercrop		Sole	Intercrop		Sole	Intercrop
pH	6.29	6.05	6.12 ^{ns}	5.28	5.16	5.37 ^{ns}	5.81	5.62	5.74 ^{ns}
SOM (%)	3.21	2.27	2.54 [*]	3.94	3.00	3.08 ^{ns}	3.56	2.62	2.79 ^{ns}
Total N (%)	0.22	0.19	0.23 [*]	0.20	0.19	0.21 ^{ns}	0.21	0.19	0.22 [*]
Available P (ppm)	33.50	35.19	35.53 ^{ns}	45.62	58.68	61.78 ^{ns}	39.27	46.94	48.66 ^{ns}
Available K (ppm)	100.58	89.98	105.78 [*]	101.36	99.27	114.95 [*]	100.95	94.40	110.36 [*]

^a Average of 20 farmers' fields at each site; ^{ns} not-significant; ^{**} P < 0.01 and ^{*} P < 0.05 at 0.05 alpha level.

The soil was moderately well drained coarse textured sandy loam with low to moderate fertility. Baseline soil samples were collected (0–20 cm depth) from farmers' fields at each test site at the time of plot establishment and analysed for pH (using a soil water solution of 1:2.5 wt/v), soil organic matter (SOM) (Walkley-Black method), total N (Modified Kjeldahl method), available P (Bray-P1 method) and available K (flame photometer with 1 M ammonium acetate extracting solution) (Anderson and Ingram, 1993). The test sites were fairly homogeneous for total N, available P and K; however, variation was observed between locations in terms of baseline soil pH and SOM (Table 1). The average pH, SOM, total N, available P₂O₅, and K₂O in Dhading were 6.29, 32.1 g kg⁻¹ dry soil, 2.2 g kg⁻¹ dry soil, 33.5 mg kg⁻¹ dry soil, and 100.6 mg kg⁻¹ dry soil, respectively, while these values were 5.28, 39.4 g kg⁻¹ dry soil, 2.0 g kg⁻¹ dry soil, 44.6 mg kg⁻¹ dry soil, and 101.4 mg kg⁻¹ dry soil in Kaski. Additional samples were taken from each plot after harvest, post two seasons (March–April, 2017), and analysed to determine changes in pH, SOM, total N, available P₂O₅, and K₂O at both sites (Table 1). The sites were used for grain (maize-millet-beans) production in prior years and managed by using farm yard manures (FYM), very low amount of chemical fertilizer (i.e., urea) and no plant protection compounds.

2.2. Experimental details

Commercial cultivars of maize (cv. Rampur Composite), wheat (cv. Gautam) and mustard (cv. Bikash) were sourced from the regional research stations of the Nepal Agricultural Research Council (NARC) while finger millet (cv. Local Dalle) was collected locally from farmers in the Dhading and Kaski districts of Nepal.

Altogether, 9 seasonal intercrop combinations (i.e., 3 in each season) were tested in year 1 (Table 2). Seasonal intercropping trials involved planting of the non-legume component as a sole crop (i.e., control) as well as growing it together with the respective legume intercrops at 20 farmers' fields per combination at each site. For example, in season 1 (i.e., spring-summer season starting mid-March to mid-July 2015), maize was grown as a sole crop as well as intercropped with cowpea (cv. Makaibodi and Suryabodi) and common bean (cv. Ghiu

Simi). In season 2 (i.e., rainy-autumn season starting mid-July to mid-November 2015), the maize sole plot was followed by the millet sole plot while maize + cowpea (cv. Makaibodi), maize + cowpea (cv. Suryabodi), and maize + bean plots were followed by millet + soybean (cv. Local Hande), millet + horsegram (cv. Local Gahat), and millet + blackgram (cv. Local Kalo Maas), respectively. Similarly, in season 3 (i.e., pre-winter through winter season starting from mid-November 2015 to mid-March 2016), mustard was grown as a sole crop after maize and millet while millet + soybean, millet + horsegram, and millet + blackgram plots were followed by mustard + field pea (cv. Arkale), wheat + field pea (cv. Arkale), and mustard + lentil (cv. Shital), respectively. For the LER calculation (please refer to Section 2.3.2), each legume which was used as an intercrop was also grown as a sole crop.

Year-round intercropping involved planting of ginger (cv. Local Bose) as a sole crop (i.e., control) as well as by under-seeding three different seasonal crops (e.g., maize, soybean, and lentil in ginger in season 1, season 2, and season 3, respectively) (Table 2). This study was conducted in 20 farmers' fields in the Kaski district only, with each farmer's field considered as a replicate.

Four seasonal intercrop combinations (i.e., maize + cowpea cv. Makaibodi, millet + soybean, mustard + pea, and wheat + pea) and a year round intercrop combination (ginger + maize in season 1 followed by under-seeding of soybean after maize harvest) that performed well in terms of yield and potential economic returns in year 1 were continued in year 2 to confirm the effect of intercrop combinations on economic yield and income (Table 2, Fig. 2). In season 3, mustard + pea was only planted in Kaski while wheat + pea was only planted in Dhading due to farmers' preferences and/or popularity of crops in the region. Across two years of study, crops were grown on the same plots under rain-fed conditions, and managed similarly across crop combinations.

Sole planting of crops involved the existing farmers' practices (i.e., behind the plough for maize and cowpea; broadcast seeding for millet, wheat, mustard, and pea; and random dibbling for ginger and soybean) (Table 3). In intercrop plots, the maize and ginger based system followed line planting (i.e., row intercropping) while the millet, wheat,

Table 2
Intercrop combinations^a in Dhading and Kaski districts of Nepal.

Year	Growing Seasons	Intercrop Combinations (n = 20 in each site)		
Year 1 (2015–2016)	Season 1 (mid-March to mid-July)	Maize + cowpea var. Makaibodi	Maize + cowpea var. Suryabodi	Maize + bean
	Season 2 (mid-July to mid-November)	Millet + soybean	Millet + horsegram	Millet + blackgram
	Season 3 (mid-November to mid-March)	Mustard + pea	Wheat + pea	Mustard + lentil
	Year-round (March 2015 to February 2016)	Ginger + maize – soybean – lentil (Kaski site only)		
Year 2 (2016–2017)	Season 1 (mid-March to mid-July)	Maize + cowpea var. Makaibodi (n = 20 in each site)		
	Season 2 (mid-July to mid-November)	Millet + soybean (n = 20 in each site)		
	Season 3 (mid-November to mid-March)	Mustard + pea (n = 20) (Kaski site only)	Wheat + pea (n = 20) (Dhading site only)	
	Year-round (March 2015 to February 2016)	Ginger + maize – soybean (Kaski site only)		

^a '+' indicates intercrop and '-' indicates the following crop in sequence.



a) Maize + cowpea



b) Millet + soybean



c) Mustard + pea



d) Wheat + pea



e) Ginger + soybean

Fig. 2. Example pictures of intercrop combinations tested in Dhading and Kaski districts in 2015–2017.

and mustard based systems followed broadcast seeding (i.e., mixed intercropping) using the seed rate as specified (Table 3). Both the sole and intercrop plots measured 6 m x 5 m. Data were collected from a 3 m x 3 m area within each plot serving as one sample.

Both legume and non-legume crops were planted by hand. Ginger, maize, cowpea, and beans were sown in early April (3–12 April 2015 and 2016), whereas millet, soybean, horsegram, and blackgram were sown in early-to-mid August (5–15 August 2015 and 2016). Wheat, mustard, pea, and lentils were seeded in mid-to-late December (15–20 December 2015 and 2016). In intercrop plots, both legumes and non-legumes were seeded the same day. Sowing depth varied with seed size and ranged from 3 to 7 cm (e.g., 3–4 cm for small seeds like millet, mustard, wheat, blackgram, horsegram, cowpea, and lentil; 4–5 cm for larger seeds like maize, soybean, field pea, and bean; and 5–7 cm for ginger). Farm yard manure (FYM) was applied at the rate of 45 kg per 30 m² (i.e., 15 t ha⁻¹) at the time of plot establishment in both sites in April (before planting maize) and in November (before planting wheat and mustard). In addition, maize plants were side dressed at knee-high stage with 0.5 kg urea per 30 m² (46-0-0, N-P-K) in both sole and intercrop plots. Sole maize plots received two manual weedings (i.e., at knee-high and tasseling stage) while the intercrop plots received one weeding only at knee-high stage. There was no need for a second weeding in the intercrop plots as the soil was covered by legume components. Similarly, millet (both sole and intercrop plots) received one weeding, 30 days after transplanting. No other fertilizers, pesticides or fungicides were used on test plots throughout the growing season.

2.3. Data collection and analysis

2.3.1. Plant-based parameters

Data were recorded for plant population, grain and biomass yield (t ha⁻¹), and harvest index [HI, defined as the ratio of economical yield (grain yield) to the total above ground biomass (grain yield + plant biomass)]. Cob, spike, pod or plant color was a determinant of maturity and considered ready for harvest when they were straw-colored, and 80% of the grains of the cob/spike/pods were in the hard-dough stage.

For widely spaced crops like maize and ginger, plants in the middle 3 m x 3 m section of each plot were harvested at maturity for yield measurements. For closely planted crops such as millet, wheat, and mustard, samples were collected from two different 1 m² areas within each plot, and averaged. Shoots of maize were harvested by hand above soil level, leaving 15–20 cm stubble whereas shoots of other crops were harvested, leaving 5–7 cm stubble; the biomass of all crops was left in the field for 5–7 days to dry and threshed separately by a stationary thresher. Seeds were dried under full sun for 5–7 days, and final seed weight was reported at 13% moisture content. Individual crop yield (grain and biomass) was calculated to permit comparison of yields, HI, total land outputs (TLOs), and land equivalent ratios (LER).

2.3.2. Relative and total intercrop productivity

System productivity was estimated using the LER which is defined as the ratio of land needed under sole cropping to produce an equal amount of yield as one of intercropping at the same management level. It compares the yield obtained by intercropping two or more species together with yields obtained by growing the same crops as sole crops. The LER for two intercrop species were calculated as follows (Mead and Willey, 1980):

$$\text{LER} = \frac{\text{intercrop yield}_{\text{non-legume}}}{\text{sole yield}_{\text{non-legume}}} + \frac{\text{intercrop yield}_{\text{legume}}}{\text{sole yield}_{\text{legume}}}$$

The yields of sole crops and intercrop species were calculated as t ha⁻¹.

Intercropped plots with LER values greater than 1.0 produced a yield advantage while plots with values less than 1.0 showed a yield disadvantage.

Table 3
Planting details for intercrop plot^a and sole plot in Dhading and Kaski districts of Nepal.

Intercrop Combination	Intercrop Plot		Sole Plot (Non-legume)	
	Planting Method	Spacing		Planting Method (Local Practice)
		Non-legume	Legume/intercrop	
Cropping Season 1 (mid-March to mid-July)				
1. Maize + cowpea var. mb 2. Maize + cowpea var. sb 3. Maize + bean	Rows of 1:1	75 cm x 30 cm	Planted between two rows of maize; in-row spacing - 15 cm	Maize (100%) seeded behind the plough
Cropping Season 2 (mid-July to mid-November)				
4. Millet + soybean 5. Millet + horsegram 6. Millet + blackgram	Broadcast	Millet (70%) and legume (30%) broadcasted and mixed into soil		Millet (100%) broadcasted uniformly across the plot and mixed into soil
Cropping Season 3 (mid-November to mid-March)				
7. Mustard + pea 8. Wheat + pea 9. Mustard + lentil	Broadcast	Mustard or wheat (70%) and legume (30%) broadcasted and mixed into soil		Mustard or wheat (100%) broadcasted uniformly and mixed into soil
Year-round (March to February)				
10. Ginger + maize – soybean – lentil	Rows of 1:1	75 cm x 20 cm	In-row spacing: maize - 30 cm soybean - 15 cm lentil - 5 cm	Ginger (100%) seeded behind the plough

^a ‘+’ indicates intercrop and ‘–’ indicates the following crop in sequence.

Intercrop productivity was also assessed in terms of Total Land Output (TLO, Jolliffe and Wanjau, 1999) as follows:

$$\text{TLO (t ha}^{-1}\text{)} = \text{Crop 1 yield (non-legume or main crop, t ha}^{-1}\text{)} + \text{Crop 2 yield (legume or intercrop, t ha}^{-1}\text{)}$$

Intercrop plots with greater TLO values compared to sole plots showed a yield advantage.

2.3.3. Net potential economic returns

Gross potential economic return from solely grown crops and intercrops were calculated using the farm gate price of the harvested commodities (grains and total plant biomass, dried). Net potential economic return was calculated as gross potential economic return less associated expenses (i.e., labour and other management costs, e.g., land preparation, fertilizers, transportation, tools and equipment, etc.) involved in sole cropping and intercropping.

2.3.4. Data analyses

The data were analyzed using GraphPad Prism 7 software (GraphPad Software, Inc. CA, USA). In order to analyze the effects of specific treatments (i.e., sole vs. intercrop) in each specific year and location, paired t-tests were performed on individual plot data for plant population, grain and biomass yields, TLO and HI. Three-way ANOVA were performed to test the main effects (i.e., treatment, year and location) and their interactions. The linear correlation and the coefficient of determination were also run between selected parameters using the Pearson Correlation Coefficient (PCC).

3. Results

3.1. Soil fertility indicators

The general trend of the post two-season soil analysis was that soil nutrient concentrations (e.g., SOM, total N, P, and K) in the sole plot were lower than the intercrop plots, at both locations, though the differences were sometimes not statistically significant (Table 1). In particular, the intercrop plots showed statistically higher soil nutrients at the Dhading site for SOM (12% higher), total N (21% higher), and K (18% higher); available K was also higher in Kaski (16% higher).

3.2. Plant performance, yield and land productivity

3.2.1. Selection of intercrop combinations

Maize + cowpea var. Makaibodi ranked first with the highest TLO (4.13 t ha⁻¹, 19% higher than the maize sole crop) and increased potential economic return (59% higher) for season 1, while the millet + soybean intercrop appeared to be the most highly productive combination for season 2 (TLO: 1.85 t ha⁻¹, 27% higher than the millet sole crop with a 326% higher net potential economic return) (Table 4). For season 3, the mustard + pea combination with a TLO of 2.1 t ha⁻¹ (i.e., 30% higher than the mustard sole crop with a 14% higher net potential economic return) was selected for Kaski while in Dhading, where farmers already preferred wheat, particularly bread wheat (unlike Kaski), the wheat + pea combination was selected for further testing based on the TLO (i.e., 2.86 t ha⁻¹, 18% higher than the wheat sole crop with a 58% higher net potential economic return). By contrast, in Kaski, where ginger was already a common crop (not in Dhading), the ginger based year round intercropping system was also selected for a second year despite statistically insignificant increases in TLO or income (Table 4), but as a result of farmer preferences over sole ginger based on community discussions.

3.2.2. Performance of selected intercrop combinations

3.2.2.1. Maize + cowpea intercropping system. The maize + cowpea strategy, including recommended spacing and line sowing, displayed a higher total plant density [8 plants per m² (4 maize + 4 cowpea) in rows compared to sole maize plots (6 maize plants per m²)] (Table 5). Compared to sole maize, the intercrop plots appeared to be more productive and potentially remunerative across locations and production years (Fig. 3a) with an average LER of 1.58 and TLO of 4.26 t ha⁻¹ (21% higher than sole maize) (Table 5). This increased farmers' potential income by 67% (i.e., from \$1310 to \$2190 per season per ha). Average maize yield was higher in the intercrop plots (3.82 t ha⁻¹) compared to sole planting (3.52 t ha⁻¹) (Table 5, Fig. 4); however, average cowpea yield was lower in the intercrop plots (0.44 t ha⁻¹ compared to 0.89 t ha⁻¹ for sole planting (Table 5, Fig. 5). The sole cowpea provided a potential net economic return of \$1380 per season per ha. The average HI for maize was greater in the intercrop plots (49% in intercrop plots vs. 46% for sole maize) (Fig. 3a). The effect of location, production years, and their interactions was not

Table 4
Intercrop combinations tested in 2015 and their performance (average across Kaski and Dhading districts).

Intercrop Combination	Intercrop Plot (t ha ⁻¹)			Sole (Non-legume) TLO ^a (t ha ⁻¹)	% Increase in TLO ^a	% Increase in Potential Income ^b	Continued in Year 2
	Non-legume	Legume	TLO ^a				
Cropping Season 1 (mid-March to mid-July)							
Maize + cowpea var. mb	3.75	0.38	4.13 ^{**}	3.47	+ 19	+ 59	YES
Maize + cowpea var. sb	3.52	0.11	3.63 ^{ns}	3.44	+ 5	+ 22	NO
Maize + bean	3.42	0.10	3.52 ^{ns}	3.58	+ 0	+ 1	NO
Cropping Season 2 (mid-July to mid-November)							
Millet + soybean	1.34	0.51	1.85 ^{**}	1.45	+ 27	+ 326	YES
Millet + horsegram	1.20	0.27	1.47 ^{ns}	1.34	+ 10	+ 90	NO
Millet + blackgram	1.39	0.00	1.39 ^{ns}	1.42	0	0	NO
Cropping Season 3 (mid-November to mid-March)							
Mustard + pea	1.69	0.41	2.10 [*]	1.62	+ 30	+ 14	YES
Mustard + lentil	1.58	0.00	1.58 ^{ns}	1.62	- 2	- 5	NO
Wheat + pea	2.46	0.40	2.86 ^{**}	2.42	+ 18	+ 58	YES
Year-round (March-February)							
Ginger + maize – soybean – lentil [†]	15.05 (ginger)		19.1 ^{ns}	18.80	+ 2	+ 5	YES
	3.45 (maize)						(see Result)
	0.62 (soybean)						
	0.00 (lentil)						

^{ns}not-significant; ^{**} P < 0.01 and ^{*} P < 0.05 at 0.05 alpha level; [†] tested in Kaski only where ‘+’ indicates intercrop and ‘-’ indicates the following crop in sequence.

^a TLO, total land output (grain yield, t ha⁻¹).

^b Based on Nepal farmgate commodity prices (USD): maize: \$0.5 per kg, makaibodi: \$2 per kg, suryabodi: \$3.5 per kg, bean: \$2.5 per kg, millet: \$0.4 per kg, soybean: \$2 per kg, horsegram: \$2 per kg, blackgram: \$1.8 per kg, mustard: \$2.5 per kg, pea: \$1 per kg, wheat: \$0.4 per kg, lentil: \$1.5 per kg, and ginger: \$0.6 per kg.

significant (Table 6); however, the grain yields, TLOs, and potential economic returns were higher in year 2 compared to year 1 at both sites (Fig. 3a; also refer to Supplementary Table A).

3.2.2.2. Millet + soybean intercropping system. In the millet + soybean intercrop plots, the total number of plants was slightly lower than the sole plots [68 plants per m² in the intercrop plots (62 millet + 6 soybeans) vs. 72 millet plants per m² in the sole plots] (Table 5). This intercrop combination appeared to be more productive and potentially remunerative across location and production years compared to sole millet (Figs. 3b, 4–5) with an average LER of 1.40 and TLO of 2.21 t ha⁻¹ (26% higher than sole millet) (Table 5). This increased farmers’ potential net income by 288% (i.e., from \$304 to \$1180 per season per ha due to the higher price of soybean). Also, sole soybean yielded 1.21 t ha⁻¹ with a higher potential net income of \$1920 per season per ha to

farmers (i.e., 532% higher than sole millet, and 62% higher than millet + soybean intercrops) (Table 5, Fig. 5). Though there was variation between years for HI (Fig. 3b), a greater average HI was observed for millet in the intercrop plots (32% for intercrop plots vs. 29% for sole crop). The effect of location and production year was found to be significant (Table 6), with greater TLOs in year 2 at both locations (Fig. 3b; also refer to Supplementary Table B). Also, grain yields and TLO were greater in Kaski compared to Dhading (Fig. 3b).

3.2.2.3. Mustard + pea intercropping system (Kaski only). The mustard + pea intercropping system resulted in a lower total number of plants [129 per m² (120 mustard + 9 pea) compared to 158 per m² in the sole plots] (Table 5). Compared to the sole mustard plots, the intercrop plots appeared to be more productive but modestly remunerative in the Kaski district (Table 5, Fig. 3c). The results from

Table 5

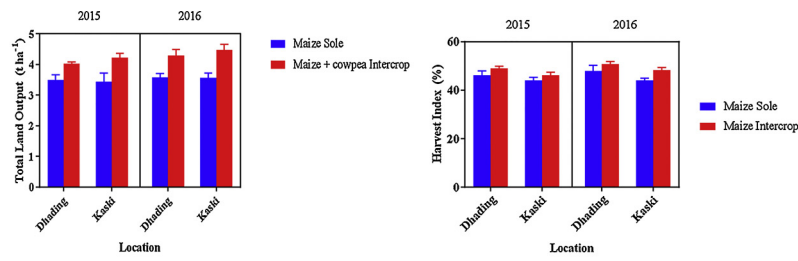
Summary of average yield, total land output (TLO, grain yield, t ha⁻¹), plant population, and land equivalent ratios (LER) for selected intercrop combinations in 2015–2017 in the Dhading and Kaski districts of Nepal.

Intercrop Combination	Intercrop Plot (t ha ⁻¹)			Sole (Non-legume) TLO (t ha ⁻¹)	% Increase in TLO	% Increase in Potential Income ^a	LER ^b
	Non-legume	Legume	TLO				
Maize + cowpea var. mb	3.82 (40)	0.44 (33)	4.26 ^{**} (73)	3.52 (56)	+ 21	+ 67	1.58
Millet + soybean	1.65 (560)	0.56 (55)	2.21 ^{**} (615)	1.76 (649)	+ 26	+ 288	1.40
Mustard + pea (Kaski)	1.71 (1083)	0.43 (82)	2.14 ^{**} (1165)	1.64 (1424)	+ 30	+ 15	1.36
Wheat + pea (Dhading)	2.49 (2360)	0.41 (90)	2.90 ^{**} (2450)	2.50 (2860)	+ 16	+ 54	1.31
Ginger + maize – soybean (Kaski)	Ginger: 17.52 (42), maize: 3.55 (38), soybean: 0.76 (52)		21.8 ^{ns} (132)	21.5 (88)	+ 2	+ 6	2.45

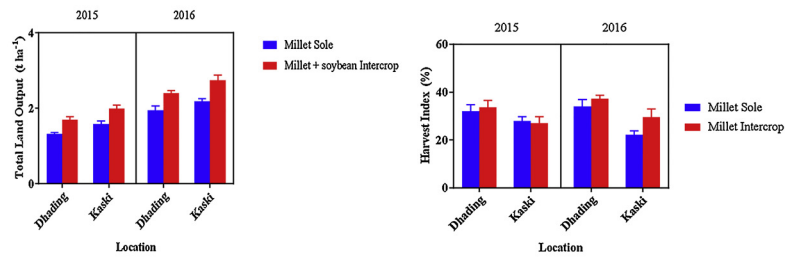
^{ns}not-significant; ^{**} P < 0.01 and ^{*} P < 0.05 at 0.05 alpha level; in intercrop combination, ‘+’ indicates intercrop and ‘-’ indicates the following crop in sequence. Figures in parenthesis indicate number of plants in 9 m² area.

^a Based on Nepal farmgate commodity prices (USD): maize: \$0.5 per kg, cowpea: \$2 per kg, millet: \$0.4 per kg, soybean: \$2 per kg, mustard: \$2.5 per kg, pea: \$1 per kg, wheat: \$0.4 per kg and ginger: \$0.6 per kg.

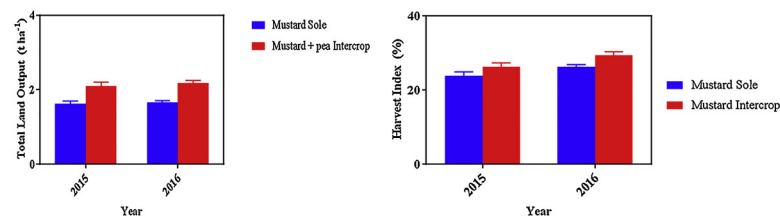
^b Grain yields from sole legumes included cowpea: 0.89 t ha⁻¹, soybean: 1.21 t ha⁻¹, and field pea: 1.33 t ha⁻¹ with plant population of 10, 21, and 27 per m², respectively.



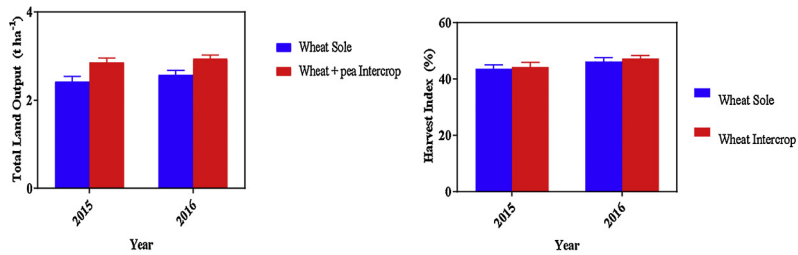
a) Maize + cowpea



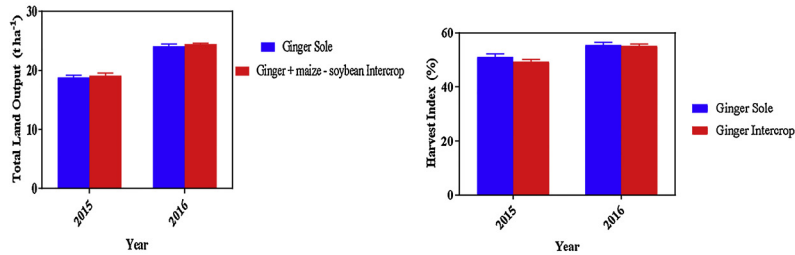
b) Millet + soybean



c) Mustard + pea



d) Wheat + pea



e) Ginger + maize - soybean

Fig. 3. Average grain yield (TLO, t ha⁻¹) and non-legume crop harvest index (%) in different intercrop combinations tested in Dhading and Kaski in 2015–2017 (error bars represent the standard error).

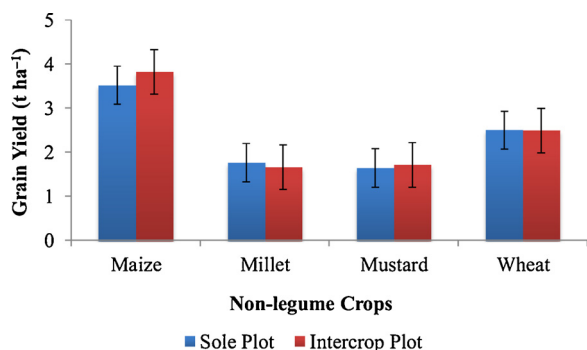


Fig. 4. Two year average grain yield of non-legume crops (t ha⁻¹) from the sole and selected intercrop plots across the two sites (error bars represent the standard error).

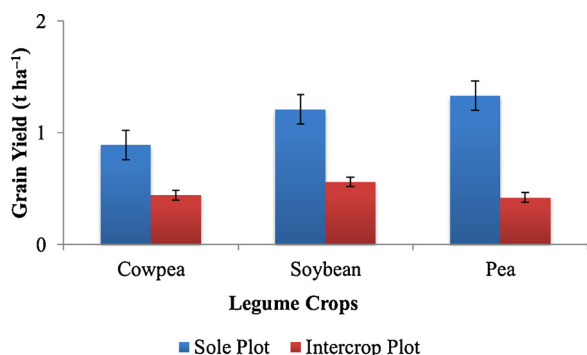


Fig. 5. Two year average grain yield of legume crops (t ha⁻¹) from selected intercrop plots and sole legume plots (from additional plots sown to calculate LER; see Methods) across the two sites (error bars represent the standard error).

this intercrop combination showed an increased average LER (1.36) and TLO (2.14 t ha⁻¹) compared to the sole crop (30% greater TLO than sole mustard) (Table 5, Fig. 3c). This increased farmers’ potential income by 15% (i.e., from \$3600 to \$4127 per season per ha) (Table 5). The sole pea yielded 1.33 t ha⁻¹ (Fig. 5) with a potential net economic return of \$947 per season per ha. This intercrop combination showed a greater HI for mustard (27% in intercrop plots vs. 25% for the sole crop) (Fig. 3c). The effect of production year and their interactions was not significant (Table 6; also refer to Supplementary Table C).

3.2.2.4. *Wheat + pea intercropping system (Dhading only)*. In Dhading, the wheat + pea intercrop plots involved fewer total number of plants than the sole plots [272 per m² (262 wheat + 10 pea) compared to 318 per m² in sole plots] (Table 5). This intercrop combination appeared to be productive and potentially remunerative than sole wheat in both production years (Fig. 3d). Across both years, the average LER for the

intercrop was 1.31 and the average TLO was 2.90 t ha⁻¹ [16% greater TLO than sole wheat, which increased the net potential economic return by 54% (i.e., from \$600 to \$927 per season per ha)] (Table 5). Sole pea also provided a higher net economic return (\$947 per season per ha i.e., 58% higher than sole wheat and 2% higher than wheat + pea intercrops). Based on the two-year average, the HI for wheat was not significantly different between intercrop and sole plots (46% for intercrop plots vs. 45% for sole plots) (Fig. 3d). The effect of location, production years, and their interactions was not significant (Table 6; also refer to Supplementary Table D).

3.2.2.5. *Ginger based intercropping system (Kaski only)*. The year-round ginger-based intercrop plots at Kaski displayed a greater total number of plants compared to the sole ginger plots [total of 15 plants per m² (5 ginger + 4 maize + 6 soybeans) compared to 10 ginger plants per m² in the sole plots] (Table 5). This combination was not significantly different in terms of TLO during 2015 and 2016 compared to sole ginger (Fig. 3e). However, due to the introduction of two new crops (i.e., maize and soybean), the two-year average LER was 2.45, with a modest increase in potential income [6% higher return to farmers (i.e., from \$12,370 to \$13,057 per year per ha)] (Table 5). The yearly and two year averaged HI for ginger was not significantly different between intercrop plots and sole ginger plots (52% in the intercrop plots vs. 54% for sole ginger) (Fig. 3e). Lentil, which was introduced as a third rotation crop after maize and soybean during the winter season, did not survive in this system, perhaps associated with shading and increased competition from ginger. In terms of the year-to-year variation, in both intercrop and sole ginger plots, the ginger yield, TLO, and LERs were greater in year 2; however, the interaction (treatment x production year) was not significant (Table 6; also refer to Supplementary Table E).

4. Discussion

Our results indicate significant yield advantages (i.e., TLO and LER) from a diversity of intercrop combinations compared to their respective sole crops on terraces in the mid-hills of Nepal. Higher yield and greater land productivity are possible when non-legume cash crops are intercropped with legumes (Masvaya et al., 2017; Jahanzad et al., 2015; Nwaogu and Muogbo, 2015; Chapagain and Riseman, 2014a, b, 2015; Chapagain, 2014; Pelzer et al., 2012; Ghaley et al., 2005; Prasad and Brook, 2005; Subedi, 1997). Prasad and Brook (2005) demonstrated higher LER (1.30 to 1.45) when maize and soybean were intercropped in the mid-hills of Nepal. Subedi (1997) also demonstrated that intercropping wheat with pea doubled the economic return than a sole wheat crop without affecting wheat yield.

Similarly, research from other regions also indicated yield and economic benefits of intercrops over monocrops. For example, Masvaya et al. (2017) demonstrated that maize + cowpea intercropped in 1:1 rows is a viable option for smallholder farms in the semi-arid environments of Southern Africa with increased yields (9–48%) and LERs

Table 6 Summary of the effects of the treatment, year and location on the total land output (TLO, grain yield, t ha⁻¹) as generated by paired t-tests.

SN	Intercrop Combination	Treatment (T)	Year (Y)	Location (L)	TxY	TxL	YxL	TxYxL
1.	Maize + cowpea var. Makaibodi	****	ns	ns	ns	ns	ns	ns
2.	Maize + cowpea var. Suryabodi	ns	n/a	ns	n/a	ns	n/a	n/a
3.	Maize + bean	ns	n/a	ns	n/a	ns	n/a	n/a
4.	Millet + soybean	****	****	***	ns	ns	ns	ns
5.	Millet + horsegram	ns	n/a	ns	n/a	ns	n/a	n/a
6.	Millet + blackgram	ns	n/a	ns	n/a	ns	n/a	n/a
7.	Mustard + pea	****	ns	n/a	ns	n/a	n/a	n/a
8.	Wheat + pea	****	ns	n/a	ns	n/a	n/a	n/a
9.	Mustard + lentil	ns	n/a	ns	n/a	ns	n/a	n/a
10.	Ginger + maize – soybean	ns	****	n/a	ns	n/a	n/a	n/a

ns not-significant; **** P < 0.0001; *** P < 0.001; ** P < 0.01 and * P < 0.05 at 0.05 alpha level; n/a = not applicable; in intercrop combination, ‘+’ indicates intercrop and ‘-’ indicates the following crop in sequence.

(1.16–1.81). Similarly, Jahanzad et al. (2015) demonstrated higher yield and LER (1.17, i.e., 17% higher) when millet and soybean were intercropped in 60:40 ratios. Chapagain and Riseman (2014a, b, 2015) and Chapagain (2014) demonstrated higher land equivalent ratios (1.49 and 1.32) and total land outputs (4.4 t ha⁻¹ and 5.9 t ha⁻¹) when wheat and barley were intercropped with beans and peas, respectively. Bulson et al. (1997) reported the highest LER value (1.29) among pure and intercropped plots when wheat and bean were intercropped at 75% of the recommended density while, Hauggaard-Nielsen et al. (2009) found a 25% to 30% grain yield increase in intercrop plots compared to monoculture plots. Sahota and Malhi (2012) also reported that intercropping barley with pea required 7–17% less land than monoculture crops to produce a comparable yield. Chen et al. (2004) compared a barley-pea intercrop system with monoculture plots and identified higher LER in the intercrop plots ranging from 1.05 to 1.24 on a biomass basis. Nwaogu and Muogbo (2015) reported that the greatest improvement in ginger yield and soil chemical attributes occurred when ginger was planted with legumes (e.g., cowpea, soybean, mungbean, and lablab) in 1:2 rows. They further demonstrated that growing a ginger:legume intercrop in more than 1:2 mixtures decreased the rhizome yield of ginger in the Guinea Savanna of Nigeria.

In the current study, it is important to note that there was a higher plant population in the intercrop plots versus sole plots in the maize-cowpea system due to line sowing at recommended spacing, etc. which might have contributed to the greater TLO from the intercrop plots. Fewer maize plants but a higher maize yield in the cowpea intercrop versus sole crop was due to a higher HI which may be attributed to possible intercrop advantages as well as a more efficient use of plant resources (i.e., water, light, and nutrients) compared to the sole plots. Also, the total plant number decreased in other intercrop combinations yet a yield gain (or greater TLO) was observed. Ideal intercrops should have complementary resource use and niche differentiation in space and time in order to optimise resource-use efficiency and crop yield simultaneously (Li et al., 2014). For example, Kermah et al. (2017) demonstrated that the sole legumes intercepted more radiation than sole maize, while the interception by intercrops was intermediary between that of sole legumes and sole maize. The intercrop, however, converted the intercepted radiation more efficiently into grain yield than the sole crops. In addition, intercropping offers several ecological benefits (see below). These factors ultimately provide greater yield advantages and potential economic return for intercrops than for sole crops.

Our results also indicate that although intercropping is beneficial, challenges may arise from strong interspecific competition for resources such as nutrients, water and light between the crops in time and space. We observed poor growth and yield of legume intercrops which were introduced late during the growing season. For example, lentil, which was introduced as a third intercrop in ginger after maize and soybean, did not survive, perhaps associated with shading and increased interspecific competition from ginger. Also, the growth and yields of field crops (both legume and non-legume) were poor in year 1 compared to year 2 which was perhaps associated with the low rainfall in year 1. Masvaya et al. (2017) reported that although greater productivity and over-yielding was observed in the intercrops compared with the sole crops, intercropping compromised cowpea yields (i.e., 5–35% lower when compared with the sole cowpea) especially under the *relay* intercrop whilst maize yield was either not affected or improved. Jeranyama et al. (2000) also reported poor cowpea yields from maize + cowpea intercrops attributed to shading by maize. Similarly, Prasad and Brook (2005) reported that high rainfall favored the growth of maize but suppressed the growth of soybean in a maize + soybean intercropping system. The competition between crops can be managed by rearranging plant populations through substitutive or additive designs to maintain productivity of the main crop (Vandermeer, 1989). Also, within-row intercropping may be more productive and lucrative compared to an inter-row system (Kermah et al., 2017), but is more

challenging to plant.

Our results from the post two-season soil analysis showed that the soil P concentrations in both the sole plot and the intercrop plots were higher than the baseline values at both locations, a surprising finding that requires further investigation. The higher post-trial P values at both sites were likely caused by achieving the recommended rates of farmyard manure [at the rate of 15 t ha⁻¹ at the time of plot establishment in both sites in April (before planting maize) and in November (before planting wheat and mustard)]. The Kaski site showed higher P and K values than Dhading. Factors that could have caused this inter-site variation include: topographical variation between the sites – sloping terrain in Dhading and comparatively flat terraces in Kaski districts, as well as climatic variation (e.g., rainfall). This could be one of the reasons why grain yields, TLO, and LER were all greater in Kaski than in Dhading. It is also important to note that the two project sites were managed by different staff due to the remoteness of the sites, but they were trained with the same protocols.

Overall, the yield advantage and associated potential economic returns from the maize + cowpea, millet + soybean, wheat + pea, mustard + pea, and ginger + maize-soybean combinations showed that the crop mixtures were more efficient than the sole cash crops particularly under low-input conditions, a situation typical to resource-poor smallholder farmers in developing countries. Masvaya et al. (2017) also demonstrated that maize + cowpea intercropping with low doses of N fertilizer resulted in over-yielding compared to the monoculture, and that such a strategy was a promising option for resource-poor farmers across seasons and soil types in developing countries.

It is important to note that this study has not assessed the additional advantages of legumes in economic terms. For example, in addition to increased land productivity and potential economic return, addition of a legume offers a number of ecological benefits including increased biological diversity and species interactions (Hauggaard-Nielsen et al., 2007), reduced soil erosion (Lithourgidis et al., 2011), increased weed suppression (Haymes and Lee, 1999; Bulson et al., 1997), increased moisture retention (Ghanbari et al., 2010), and maintenance of soil fertility through the legume-rhizobia symbiosis (Chapagain and Riseman, 2014a, 2015; Chapagain, 2014; Hauggaard-Nielsen et al., 2009, 2003; Bulson et al., 1997; Jensen, 1996). As a result, the combination of a non-leguminous species with a leguminous species is expected to provide yield advantages over single species cropping (Ofori and Stern, 1987; Trenbath, 1974). Hence, growing small grains with grain legumes under low input farming practices is seen as a strong component of a farm-wide production system that fulfills economic and environmental sustainability concerns (Chapagain and Riseman, 2014a, b, 2015; Chapagain, 2014; Chapagain and Riseman, 2012).

5. Summary and conclusions

This study identified a menu of intercropping options that appeared to be robust across seasons and locations, providing a range of options for resource-poor smallholder farmers in the mid-hills of Nepal which may be applicable to other developing countries. For the spring-summer season (i.e., mid-March to mid-July), maize + cowpea var. Makaibodi appeared to be the most productive with an average TLO (4.26 t ha⁻¹ i.e., 21% higher than the sole maize) and LER (1.58) which increased farmers' potential income by 67%. For the rainy-autumn season (i.e., mid-July to mid-November), millet + soybean appeared to be productive with an average TLO (2.21 t ha⁻¹ i.e., 26% higher than the sole millet) and LER (1.40), which increased farmers' potential net income by 288%. Similarly during the pre-winter/winter season (i.e., mid-November to mid-March), mustard + pea with an average TLO (2.14 t ha⁻¹ i.e., 30% higher than the sole mustard) and LER (1.36) appeared to be productive in Kaski. This increased farmers' potential income by 15%. In the meantime, wheat + pea appeared to be productive in Dhading with an average TLO of 2.90 t ha⁻¹ (16% higher than the sole wheat) and LER of 1.31, which increased the net potential

economic return by 54%. In Kaski, the ginger-based year-round combination also appeared to be productive with an average TLO of 21.8 t ha⁻¹ (2% higher than the sole ginger) and LER of 2.45 which increased the net potential economic return by 6%. However, lentil, which was introduced as a third crop in rotation after maize and soybean, did not survive in this system perhaps associated with shading from ginger. It is important to note that soybean and pea provided higher potential net income to farmers as sole crops compared to when they are grown with millet and wheat as intercrops, respectively.

Despite there being a number of benefits to including legumes as intercrops (e.g., increasing land productivity and potential economic return, reduction of external inputs such as nitrogen fertilizers, their ability to serve as cover crops for conservation of soil moisture, providing protein and micronutrient rich grains to local households and nutrient rich fodder for livestock, etc.), there are also some challenges. These include: 1) challenges in tailoring specific production practices of any particular crop as there are many crops planted together in the field; 2) difficulties in mechanizing field-level tasks (e.g., planting, harvesting, weeding, etc.) especially in a mixed system which may demand more labour than sole cropping; 3) constraints in applying chemical weed control due to potential deleterious effects on other crops in the combination; and 4) poverty and illiteracy in remote rural areas of developing countries. Nevertheless, improved intercropping could be a promising ecological practice for low external input smallholder agriculture in the hills and mountains where on-farm mechanization is already constrained by the topology and where agriculture is already reliant upon animal and human labour. However, moving into the future, effective dissemination and adoption of novel intercropping strategies, particularly on medium to large farms, will require mechanization (i.e., multi-screened harvesters) and participatory trials to inform farmers of the advantages of different legume integration strategies with respect to land productivity, soil fertility management, and profit. Such strategies could be supported by formalized government policies to diversify terrace agriculture and support for organizations dedicated to the well-being of terrace farmers and ecosystems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.fcr.2018.07.016>.

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