**Seasonal and Year-round Intercropping Systems for Smallholder Farmers: Results from On-farm Intercropping Trials on Terraces in Nepal on Maize, Millet, Mustard, Wheat and Ginger**

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## Abstract

Low yield and total land productivity are major challenges associated with smallholder terrace agriculture in developing countries. Crop intensification and diversification by introducing legumes as intercrop could help alleviate these challenges. We compared 10 intercrop combinations with sole cropping system for two rotation cycles (2015-17) to identify the most productive and economic intercrop combinations for smallholder terrace agriculture. In the spring-summer season (March/April-July/August), cowpea (var. Makaibodi and Suryabodi) and bean were intercropped with maize in rows of 1:1 whereas soybean, blackgram and horsegram were broadcasted with millet (30:70 ratios) during summer-rainy season (July/August-November/December). Pea and lentil were used as winter intercrop (November/December-March/April) in wheat (30:70 ratios) while mustard was planted with pea. Ginger was planted with maize in 1:1 rows during spring-summer season in which the maize rows were replaced by soybean and lentil during summer-rainy and winter season, respectively.

Intercropping appeared to be a robust option across seasons and soil types confirming that it could a promising practice for resource-poor smallholder farmers. Maize + cowpea var. Makaibodi appeared to be the most productive and economic intercrop combination for spring-summer season (LER - 1.64 and TLO - 4.43 t $ha^{-1}$, 26% higher than the maize sole crop with an increase of potential economic return by 64%) whereas millet + soybean appeared as the best combination for summer-rainy season (LER - 1.40 and TLO - 2.21 t $ha^{-1}$, 26% higher than the millet sole crop that increased potential income by 154%). For winter, wheat + pea (LER - 1.31 and TLO - 2.90 t $ha^{-1}$ i.e., 16% higher than wheat sole crop which increased potential economic return by 30%) and mustard + pea combinations (LER - 1.36 and TLO - 2.14 t $ha^{-1}$ i.e., 30% higher than mustard sole crop with an increase of potential income by 12%) appeared to be productive. Year round intercrop system (i.e., ginger + maize-soybean) displayed a LER value of 2.69 with increased TLO (22.2 t $ha^{-1}$ i.e., 2% higher compared to when ginger was cultivated alone) which increased potential economic return by 11%. It is hoped that these studies provide

farmers an opportunity to choose the most productive and economic intercrop combinations, both seasonal as well as year-round, depends on their needs and interests.

**Key words:** Intercropping, Seasonal, Year-round, Total Land Productivity, Terrace agriculture, Nepal

## 1. Introduction

Intercropping is when two or more than two crops are planted together on the same land (Ofori and Stern, 1987). Intercropping can be of row, mixed, relay and strip depend 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, unlike row planting (Chapagain, 2014, 2016; Chapagain and Riseman, 2014a, 2015). The third type (i.e., relay intercropping) is when the second crop is planted/introduced before the first one is ready to harvest, especially during reproductive stage of the first crop, to utilize shorter growing seasons. Stripe intercropping refers to growing of two or more crops in stripes which are wide enough to permit intercultural operation but narrow enough to interact agronomically (Sharma et al., 2001). Typically, intercrop components are from different species or families with one crop of primary importance (e.g., food production) while the other primarily providing additional benefits (e.g., $N_2$ fixation for legume species). An effective intercrop combination is one that produces greater total yield on a piece of land and uses resources more efficiently than would otherwise be used when each crop is grown as a monoculture (Inal et al., 2007).

Intercropping offers several ecological benefits including increasing biological diversity, promoting species interaction and enabling natural regulation mechanisms (Hauggaard-Nielsen et al., 2007). Also, addition of legume provide a number of additional benefits to soil quality including reducing soil erosion (Lithourgidis et al., 2011), increasing weed suppression (Bulson et al., 1997; Haymes and Lee, 1999), increasing moisture retention (Ghanbari et al., 2010), maintaining soil fertility through the legume-rhizobia symbiosis (Chapagain, 2014; Hauggaard-Nielsen et al., 2009), increasing nutrient cycling (Chapagain and Riseman, 2014a, 2015; Hauggaard-Nielsen et al., 2003; Jensen, 1996) and biological nitrogen fixation (Bulson et al., 1997; Chapagain and Riseman, 2014a, 2015). It produces an opportunity to improve agriculture through sustained production (Hauggaard-Nielsen et al., 2007), enhanced soil conservation (Lithourgidis et al., 2011) and significant labor savings (Thurston, 1996). As a result, the combination of a non-leguminous species with a leguminous species is expected to produce yield advantages over single species cropping (Ofori and Stern, 1987; Trenbath, 1974). Hence, growing small grains with grain legumes under low input organic farming practices is seen as a strong component of a farm-wide production system that fulfills economic and environmental sustainability concerns (Chapagain and Riseman, 2012).

In Nepal, a fairly large section of farmers are subsistence with average farm holdings of 0.8 ha (CBS, 2011). Farming in hills and mountains involves rainfed terrace farming with low external inputs (Chapagain and Raizada, 2017a; Riley et al., 1990; Wymann von Dach et al., 2013) and integration of crops and livestock (Subedi, 1997). Farmers harvest 2-3 crops in a year depend on farmers decisions, which are conditioned by multiple drivers such as climate, soil type(s), topography, land holdings, farmer's needs, cultural preferences, availability of agricultural inputs (e.g. seeds, fertilizers, etc.), and local market opportunities (Chapagain and Raizada, 2017a; Riley et al., 1990). These regions are characterized by having limited land area for agriculture, increased erosion and loss of soil fertility, low yield, poor access to agricultural inputs and services, shortage of irrigation water, and lack of mechanization and labour shortages (Chapagain and Gurung, 2010; Chapagain and Raizada, 2017a) which can be addressed by appropriate agronomic strategies that are diverse and compatible with the growing season and location (Chapagain and Raizada, 2017a, b). Intercropping is considered as one of the agro-ecological approaches for terrace intensification that enhance productivity and environmental sustainability (Chapagain and Raizada, 2017a).

The hill farmers in Nepal grow cereals as their staple diet. Therefore, the principal field crops in hills and mountains include: maize (*Zea mays* L.), finger millet (*Eleusine coracana* L.), wheat (*Triticum aestivum* L.) and mustard (*Brassica nigra* L.) (Chapagain and Raizada, 2017a). These crops are mostly grown as sole crop during spring-summer (i.e., March/April-July/August: maize), summer-rainy (i.e., July/August-November/December: millet) and winter/early spring seasons (i.e., November/December-March/April: mustard, wheat). Legumes, such as, cowpea (*Vigna ungiculata* 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 depending on the season and farmers' interest (Chapagain and Gurung, 2010; Chapagain and Raizada, 2017a). Ginger (*Zingiber officinale* Roscoe), which takes ~10 months to mature, is also a popular cash/spice crop in mid-hill regions. Some legumes, such as, cowpea, soybean and pea are grown as intercrop sporadically across Nepal; however, very little attention has been given to identify the most productive and economic intercrop combinations through systemic on-farm trials (Subedi, 1997). This research explores the opportunities to use legumes as intercrop in maize, millet, wheat, mustard and ginger, and offers the most productive and economic intercrop combination(s) for each season.

## 2. Materials and Methods

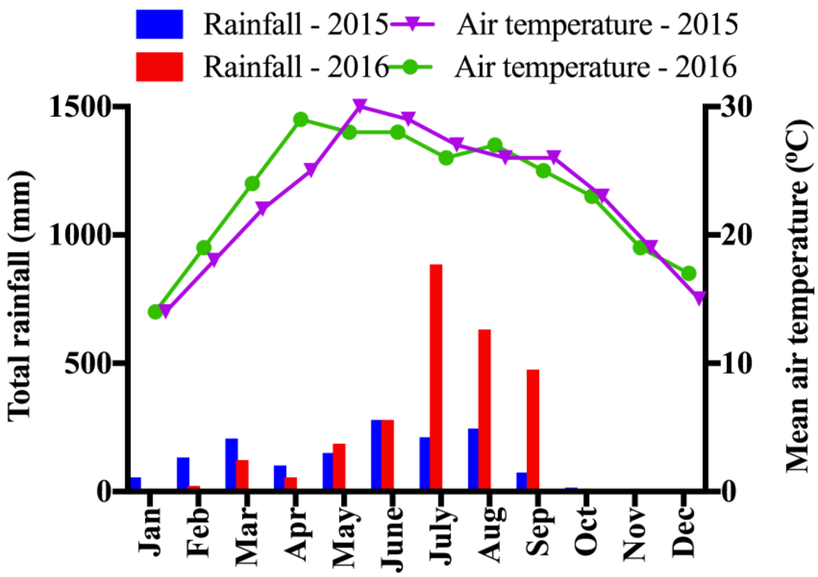
### 2.1 Study site, climate and soil description

This study was conducted in two mid-hill districts of Nepal namely, Dhading and Kaski, for two rotation cycles 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 meters 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 at farmers' fields under natural climatic conditions.

Climatic data for the experiment were collected from a regional weather station at the research site (Figure 1). Average day-time temperature over the three cropping seasons (April-July, August-November and December-March) were 27.8$^0$C, 23.5$^0$C, and 18.3$^0$C in Dhading and 24.4$^0$C, 21.9$^0$C, and 16.3$^0$C in Kaski with the warmest days in May thru August at both sites. Both Dhading and Kaski received more rainfall (annual total of 2660 mm and 3459 mm, respectively) in 2016, with season 1 (i.e., April-July) receiving the most (1408 mm and 1758 mm, respectively). Both sites received the least rainfall in winter (October-February), receiving no rains in November-December (Figure 1).

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 average pH, SOM, total N, available $P_2O_5$ and $K_2O$ in Dhading were 6.29, 321 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, 394 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 (Spring, 2017), and analysed to determine changes in pH, SOM, total N, available $P_2O_5$ and $K_2O$ at both sites (Table 2). 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.

A. Dhading




B. Kaski

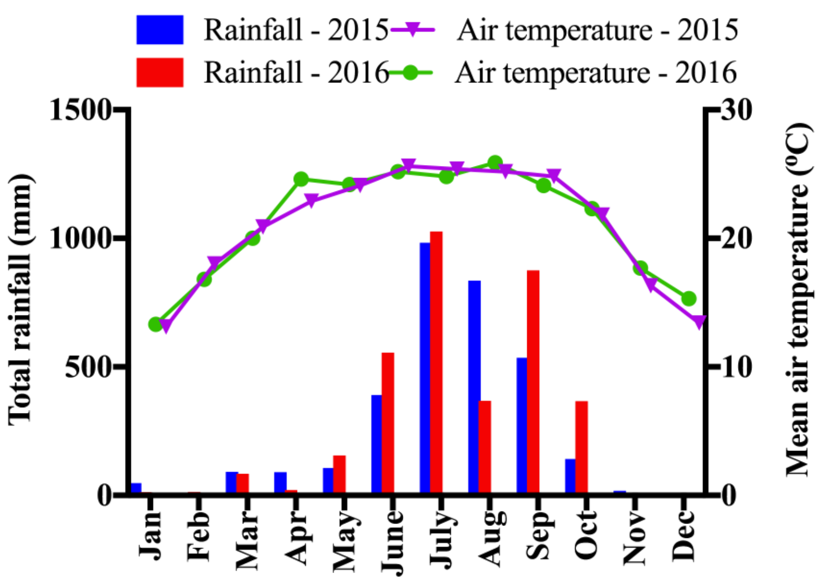



**Figure 1:** Climatic data (air temperature and rainfall) collected for (A) Dhading and (B) Kaski districts in 2015 and 2016.

## 2.2 Experimental details

Commercial cultivars of maize (*Zea mays* cv. Rampur Composite), wheat (*Triticum aestivum* cv. Gautam) and mustard (*Brassica nigra* cv. Bikash) were sourced from the regional research stations of the Nepal Agricultural Research Council (NARC) while finger millet (*Eleusine coracana* 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 1). Seasonal intercropping trials involved planting of the non-legume component as a sole crop (i.e., control) as well as growing it together with suitable legume crops (i.e., intercrop) at 20 farmers' fields per combination in each site. For example, in season 1 (i.e., spring-summer season starting March/April to July/August, 2015), maize was grown as a sole crop as well as intercropped with cowpea (*Vigna ungiculata* cv. Makaibodi and Suryabodi) and common bean (*Phaseolus vulgaris* cv. Ghiu Simi) while the millet was planted as a sole crop as well as intercropped with soybean (*Glycine max* cv. Local Hande), horsegram (*Macrotyloma uniflorum* cv. Local Gahat), and blackgram (*Vigna mungo* cv. Local Kalo Maas) in season 2 (i.e., summer-rainy season starting July/August to November/December, 2015). Similarly, mustard was grown as a sole crop in season 3 (i.e., winter thru early spring season starting from November/December, 2015 to March/April, 2016) as well as intercropped with field pea (*Pisum sativum* cv. Arkale) and lentil (*Lens culinaris* cv. Shital). Wheat was only planted in Dhading as a sole crop and was intercropped with field pea due to farmers' preferences and/or popularity of bread wheat in the region. 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 (*Zingiber officinale* cv. Local Bose) as a sole crop (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). Maize, soybean and lentil were also grown as sole crops to calculate LER. This study was conducted in 20 farmers' fields in the Kaski district, 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. Across two years of study, crops were grown on the same plots under rain-fed conditions, and managed similarly across 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). In intercrop plots, the maize and ginger based system followed line planting (i.e., row intercropping) while the millet, wheat and mustard based systems followed broadcast seeding (i.e., mixed intercropping) using the seed rate as specified (Table 1). Both the control and intercrop plots measured 6 m x 5 m. Data were collected from 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, legumes were seeded the same day. Sowing depth varied with seed size and ranged from 3-7 cm (e.g., 3-4 cm for small seeds like millet, mustard, wheat, blackgram, horsegram, cowpea, 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 $m^2$ (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 $m^2$ (46-0-0, N-P-K) in both control and intercrop plots. Maize plots received two manual weeding (i.e., at knee-high and tasseling stage) while millet received one weeding, 30 days after transplanting. No other fertilizers, pesticides or fungicides were used on test plots throughout the growing season.

**Table 1:** Intercrop combinations and planting details in Dhading and Kaski districts of Nepal.

| Intercrop Combination | Intercrop Plot | | | Control (Non-legume) |
|---|---|---|---|---|
| | Planting Method | Spacing | | Planting Method (Local Practice) |
| | | Non-legume | Legume/intercrop | |
| **Season 1 (March/April to July/August)** | | | | |
| 1. Maize + cowpea var. mb<br>2. Maize + cowpea var. sb<br>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 |
| **Season 2 (July/August to November/December)** | | | | |
| 4. Millet + soybean<br>5. Millet + horsegram<br>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 |
| **Season 3 (November/December to March/April)** | | | | |
| 7. Mustard + pea<br>8. Wheat + pea<br>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:<br>maize - 30 cm<br>soybean - 15 cm<br>lentil - 5 cm | Ginger (100%) seeded behind the plough |

## 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 $m^2$ 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 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) with those when they were grown alone.

### 2.3.2 Relative and total intercrop productivity

System productivity was estimated using the Land Equivalent Ratio (LER) which 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):

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

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.

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

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

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). Three-way ANOVA were performed to test the main effects (i.e., treatment, year and location) and their interactions. In order to analyze the effects of specific treatments (i.e., control 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. 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 measurements

Variation was observed between locations in terms of baseline soil pH (6.29 vs. 5.28 in Dhading and Kaski, respectively) and SOM (3.21 vs. 3.94% in Dhading and Kaski, respectively); however, these sites were fairly homogeneous for total N, available P and K (Table 2). 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 control plot (i.e. sole crop) were lower than the intercrop plots, at both locations, though the differences were sometimes not statistically significant (Table 2). In particular, the intercrop plots showed statistically higher soil nutrients at the Dhading site for SOM (from 2.27% to 2.54%, i.e., 12% higher), total N (from 0.19% to 0.24%, i.e., 26% higher), and K (from 89.9 ppm to 105.8 ppm, i.e., 18% higher); available K was also higher in Kaski (from 99.3 to 114.9 ppm, i.e., 16% higher).

**Table 2:** Baseline and post 2-season soil fertility measurements† from non-legume sole crop (control) 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 | |
| | | Control | Intercrop | | Control | Intercrop | | Control | 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 | 0.24$^{*}$ | 0.20 | 0.21 | 0.23 $^{ns}$ | 0.21 | 0.20 | 0.24$^{*}$ |
| 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$^{*}$ |

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

### 3.2 Plant performance, yield and land productivity

#### 3.2.1 Selection of intercrop combinations

Among 10 intercrop combinations tested in Kaski and Dhading in year 1, the combination(s) with the highest land productivity and increased potential economic return were selected for further evaluation in year 2 (Table 3). Maize + cowpea var. Makaibodi ranked first with the highest TLO (4.30 t ha$^{-1}$, 24% higher than the maize sole crop) and increased potential economic return (57% higher) for season 1 (March/April-July/August) while the millet + soybean intercrop appeared to be the most highly productive combination for season 2 (July/August-November/December) (TLO: 1.85 t ha$^{-1}$, 27% higher than the millet sole crop with a 167% higher net potential economic return). For season 3 (i.e., November/December-March/April), mustard + pea combination with a TLO of 2.10 t ha$^{-1}$ (i.e., 29% higher than the mustard sole crop) was selected for both locations. In Dhading, where farmers already preferred wheat, particularly bread wheat (unlike Kaski), the wheat + pea combination was also selected for further testing based on the TLO (i.e., 2.86 t ha$^{-1}$, 18% higher than the wheat sole crop). 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 3), but as a result of farmer preferences over sole ginger based on community discussions.

**Table 3:** Intercrop combinations tested in 2015 and their performance (average across Kaski and Dhading districts).

| Intercrop Combination | Intercrop Plot (t ha$^{-1}$) Non-legume | Legume | TLO | Control (Non-legume) TLO (t ha$^{-1}$) | % Increase in TLO | % Potential Increase in Income[#] | Continued in Year 2 |
|---|---|---|---|---|---|---|---|
| **Season 1 (March/April-July/August)** | | | | | | | |
| Maize + cowpea var. mb | 3.92 | 0.38 | 4.30$^{**}$ | 3.47 | + 24 | + 57 | YES |
| Maize + cowpea var. sb | 3.89 | 0.11 | 4.00$^{ns}$ | 3.44 | + 16 | + 35 | NO |
| Maize + bean | 3.42 | 0.10 | 3.52$^{ns}$ | 3.58 | + 0 | + 9 | NO |
| **Season 2 (July/August-November/December)** | | | | | | | |
| Millet + soybean | 1.34 | 0.51 | 1.85$^{**}$ | 1.45 | + 27 | + 167 | 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 |
| **Season 3 (November/December to March/April)** | | | | | | | |
| Mustard + pea | 1.69 | 0.41 | 2.10$^{*}$ | 1.64 | + 29 | + 11 | YES |
| Mustard + lentil | 1.58 | 0.00 | 1.58$^{ns}$ | 1.62 | - 2 | - 2 | NO |
| Wheat + pea[†] | 2.46 | 0.40 | 2.86$^{**}$ | 2.42 | + 18 | + 33 | YES |
| **Year-round (March-February)** | | | | | | | |
| Ginger + maize-soybean-lentil[††] | 14.05 (ginger) 3.92 (maize) 0.92 (soybean) 0.00 (lentil) | | 18.89$^{ns}$ | 18.80 | + 1 | + 8 | YES (see Result) |

$^{ns}$not-significant; $^{**}$P <0.01 and $^{*}$P <0.05 at 0.05 alpha level; TLO, total land output (grain yield, t ha$^{-1}$); [†]tested in Dhading only; [††]tested in Kaski only.

[#]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: $0.75 per kg, wheat: $0.4 per kg, lentil: $1.5 per kg, and ginger: $0.6 per kg.

### 3.2.2 Performance of selected intercrop combinations

***Maize + cowpea intercropping system:***

The maize + cowpea strategy, including recommended spacing and line sowing, displayed a higher total plant density [8 plants per m$^2$ (4 maize + 4 cowpea) in rows compared to maize alone [6 maize plants per m$^2$ in control plots]. Compared to maize alone, the intercrop plots appeared to be more productive and potentially remunerative across locations and production years (Table 4, Figure 2a) with an average LER of 1.64 and TLO of 4.43 t ha$^{-1}$ (26% higher than sole maize with 64% higher potential economic return to farmers). Average maize yield was higher in the intercrop plots (3.74 t ha$^{-1}$) compared to sole planting (3.54 t ha$^{-1}$) (Table 4, Figure 3); however, average cowpea yield was lower in the intercrop plots (0.4 t ha$^{-1}$ compared to 0.9 t ha$^{-1}$ for sole planting; Figure 4). The average HI for maize was greater in the intercrop plots (49% in intercrop plots vs. 46% for sole maize). The effect of location, production years and their interactions was not significant (Table 10); however, the grain yields, TLOs and potential economic returns were higher in year 2 compared to year 1 at both sites (Table 4).

**Table 4:** Yield, total land outputs (TLO, grain yield, t ha$^{-1}$), plant population, harvest index (HI, %) and land equivalent ratios (LER) from the maize + cowpea system in 2015-2016 in Dhading and Kaski districts of Nepal.

| Year | Intercrop Plot (t ha$^{-1}$) | | | Control (Sole maize) TLO (t ha$^{-1}$) | Maize Harvest Index (%) | | % Increase in TLO | % Potential Increase in Income[#] | LER |
|---|---|---|---|---|---|---|---|---|---|
| | Maize | Cowpea | TLO | | Sole | Intercrop | | | |
| **DHADING** | | | | | | | | | |
| Year 1 | 3.74 (38) | 0.39 (28) | 4.13$^{**}$ (66) | 3.54 (55) | 46 | 49$^{*}$ | + 17 | + 50 | 1.56 |
| Year 2 | 3.92 (40) | 0.52 (30) | 4.44$^{**}$ (70) | 3.63 (56) | 48 | 51$^{*}$ | + 22 | + 65 | 1.58 |
| **KASKI** | | | | | | | | | |
| Year 1 | 4.10 (38) | 0.37 (32) | 4.47$^{**}$ (70) | 3.40 (56) | 43 | 46$^{*}$ | + 32 | + 64 | 1.68 |
| Year 2 | 4.18 (42) | 0.49 (41) | 4.67$^{**}$ (83) | 3.53 (57) | 44 | 48$^{**}$ | + 32 | + 74 | 1.71 |

$^{ns}$not-significant, $^{**}$P <0.01 and $^{*}$P <0.05 at 0.05 alpha level;

Figures in parenthesis indicate average number of plants in 9 m$^2$ area;

[#]based on Nepal farmgate commodity prices (USD): maize: $0.5 per kg, cowpea: $2 per kg.

***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 m$^2$ in the intercrop plots (63 millet + 5 soybeans) vs. 72 millet plants per m$^2$ in the control plots]. This intercrop combination appeared to be more productive and potentially remunerative across location and production years compared to sole plots (Table 5, Figure 2b, Figures 3-4) with an average LER of 1.40 and TLO of 2.21 t ha$^{-1}$ (26% higher than the sole millet, resulting in a 154% higher potential return to farmers) (Table 9). Though there was variation between years for HI (Table 5), a greater average HI was observed for millet in the intercrop plots (32% for intercrop plots vs. 29% for control crop) (Table 9). The effect of location and production year was found to be significant (Table 10), with greater TLOs in year 2 at both locations (Table 5). Also, grain yields and TLO were greater in Kaski compared to Dhading (Table 5).

**Table 5:** Yield, total land outputs (TLO, grain yield, t ha$^{-1}$), plant population, harvest index (HI, %) and land equivalent ratios (LER) from the millet + soybean system in 2015-2016 in Dhading and Kaski districts of Nepal.

| Year | Intercrop Plot (t ha$^{-1}$) | | | Control (Sole millet) TLO (t ha$^{-1}$) | Millet Harvest Index (%) | | % Increase in TLO | % Potential Increase in Income[#] | LER |
|---|---|---|---|---|---|---|---|---|---|
| | Millet | Soybean | TLO | | Sole | Intercrop | | | |
| **DHADING** | | | | | | | | | |
| Year 1 | 1.27 (540) | 0.43 (44) | 1.70$^{*}$ (584) | 1.32 (618) | 32 | 34$^{ns}$ | + 29 | + 159 | 1.33 |
| Year 2 | 1.82 (552) | 0.58 (50) | 2.40$^{**}$ (602) | 1.95 (639) | 34 | 37$^{*}$ | + 23 | + 142 | 1.40 |
| **KASKI** | | | | | | | | | |
| Year 1 | 1.40 (556) | 0.59 (47) | 1.99$^{**}$ (603) | 1.58 (632) | 28 | 27$^{ns}$ | + 26 | + 175 | 1.39 |
| Year 2 | 2.10 (606) | 0.64 (52) | 2.74$^{**}$ (658) | 2.18 (686) | 22 | 29$^{**}$ | + 26 | + 143 | 1.46 |

$^{ns}$not-significant; $^{**}$P <0.01 and $^{*}$P <0.05 at 0.05 alpha level;

Figures in parenthesis indicate number of plants in 9 m$^2$ area;

[#]based on Nepal farmgate commodity prices (USD): millet: $0.4 per kg, soybean: $2 per kg.

***Mustard + pea intercropping system:***

The mustard + pea intercropping system resulted in a lower total number of plants [162 per m$^2$ (157 mustard + 5 pea) compared to 190 per m$^2$ in control plots] (Table 6). Compared to the sole crop plots, the intercrop plots appeared to be more productive but modestly remunerative at both Kaski and Dhading districts (Table 6). The results from this intercrop combination (Table 6, Figure 2c, Figures 3-4) 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, resulting in 12% greater potential economic return to farmers) (Table 9). This intercrop combination showed a greater HI for mustard (27% in intercrop plots vs. 25% for the sole crop). The effect of location was statistically significant, with greater yield and TLOs in Kaski (Table 6); however the effect of production year and their interactions was not-significant (Table 10).

**Table 6:** Yield, total land outputs (TLO, grain yield, t ha$^{-1}$), plant population, harvest index (HI, %) and land equivalent ratios (LER) from the mustard + pea system in 2015-2016 in Dhading and Kaski districts of Nepal.

| Year | Intercrop Plot (t ha$^{-1}$) | | | Control (Sole Mustard) TLO (t ha$^{-1}$) | Mustard Harvest Index (%) | | % Increase in TLO | % Potential Increase in Income[#] | LER |
|---|---|---|---|---|---|---|---|---|---|
| | Mustard | Pea | TLO | | Sole | Intercrop | | | |
| **DHADING** | | | | | | | | | |
| Year 1 | 1.58 | 0.40 | 1.98$^{*}$ | 1.49 | 25 | 26$^{ns}$ | + 33 | + 14 | 1.36 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1.53<br>(1357) | (38) | (1395) | (1611) | | | | | |
| Year 2 | 1.69<br>(1382) | 0.42<br>(42) | $2.11^{*}$<br>(1424) | 1.58<br>(1720) | 26 | $29^{*}$ | + 34 | + 15 | 1.38 |
| **KASKI** | | | | | | | | | |
| Year 1 | 1.80<br>(1332) | 0.42<br>(42) | $2.22^{*}$<br>(1374) | 1.78<br>(1705) | 22 | $25^{*}$ | + 25 | + 8 | 1.33 |
| Year 2 | 1.78<br>(1581) | 0.46<br>(44) | $2.24^{*}$<br>(1625) | 1.70<br>(1830) | 26 | $28^{ns}$ | + 32 | + 13 | 1.38 |

$^{ns}$not-significant; $^{**}$P <0.01 and $^{*}$P <0.05 at 0.05 alpha level;

Figures in parenthesis indicate number of plants in 9 $m^2$ area;

#based on Nepal farmgate commodity prices (USD): mustard: $2.5 per kg, pea: $0.75 per kg.

***Wheat + pea intercropping system (Dhading only):***

In Dhading, the wheat + pea intercrop plots involved fewer total number of plants than the sole plots [472 per $m^2$ (466 wheat + 6 pea) compared to 518 per $m^2$ in control plots]. This intercrop combination appeared to be productive and potentially remunerative than sole wheat in both production years (Table 7, Figure 2d, Figures 3-4). 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, providing a 30% higher potential return to farmers) (Table 9). 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). The effect of location, production years and their interactions was not significant (Table 10).

**Table 7:** Yield, total land outputs (TLO, grain yield, t $ha^{-1}$), plant population, harvest index (HI, %) and land equivalent ratios (LER) from the wheat + pea system in 2015-2016 in the Dhading district of Nepal.

| **Year** | **Intercrop Plot (t $ha^{-1}$)** | | | **Control (Sole wheat) TLO (t $ha^{-1}$)** | **Wheat Harvest Index (%)** | | **% Increase in TLO** | **% Potential Increase in Income#** | **LER** |
|---|---|---|---|---|---|---|---|---|---|
| | **Wheat** | **Pea** | **TLO** | | **Sole** | **Intercrop** | | | |
| Year 1 | 2.46<br>(4282) | 0.40<br>(47) | $2.86^{**}$<br>(4329) | 2.42<br>(4611) | 44 | $44^{ns}$ | + 18 | + 33 | 1.33 |
| Year 2 | 2.52<br>(4111) | 0.42<br>(51) | $2.94^{*}$<br>(4162) | 2.58<br>(4725) | 46 | $47^{ns}$ | + 14 | + 28 | 1.29 |

$^{ns}$not-significant; $^{**}$P <0.01 and $^{*}$P <0.05 at 0.05 alpha level;

Figures in parenthesis indicate number of plants in 9 $m^2$ area;

#based on Nepal farmgate commodity prices (USD): wheat: $0.4 per kg, pea: $0.75 per kg.

a) Maize + cowpea

b) Millet + soybean

c) Mustard + pea

d) Wheat + pea

e) Ginger + soybean

**Figure 2:** Example pictures of intercrop combinations tested in Dhading and Kaski in 2015/2016.

***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 16 plants per $m^2$ (5 ginger + 5 corn + 6 soybean) compared to 8 ginger plants per $m^2$ in control plots]. This combination was not significantly different in terms of TLO during 2015 and 2016 compared to sole ginger (Table 8, Table 9, Figure 2e). However, due to the introduction of two new crops (maize, soybean), the two-year average LER was 2.69, with a modest increase in potential income (11% higher return to farmers) (Table 9). The yearly (Table 8) and two year averaged (Table 9) HI for ginger was not significantly different between intercrop plots and sole ginger plots (52% in the intercrop plots vs. 54% for sole ginger). 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 8, 10).

**Table 8:** Yield, total land outputs (TLO, grain yield, t $ha^{-1}$), plant population, harvest index (HI, %) and land equivalent ratios (LER) from the ginger-based intercropping system in the Kaski district of Nepal.

| Year | Intercrop Plot (t $ha^{-1}$) | | | | | Control (Sole ginger) TLO (t $ha^{-1}$) | Ginger Harvest Index (%) | | % Increase in TLO | % Potential Increase in Income# | LER |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ginger | Maize | Soybean | Lentil | TLO | | Sole | Intercrop | | | |
| Year 1 | 14.05 (36) | 3.92 (39) | 0.92 (49) | 0 | $18.9^{ns}$ (124) | 18.8 (57) | 51 | $49^{ns}$ | + 1 | + 8 | 2.58 |
| Year 2 | 19.98 (47) | 4.10 (46) | 1.49 (54) | 0 | $25.6^{ns}$ (147) | 25.1 (80) | 56 | $55^{ns}$ | + 2 | + 13 | 2.81 |

$^{ns}$not-significant; $^{**}P<0.01$ and $^{*}P<0.05$ at 0.05 alpha level;

Figures in parenthesis indicate number of plants in 9 $m^2$ area;

#based on Nepal farmgate commodity prices (USD): ginger: $0.6 per kg, maize: $0.5 per kg and soybean: $2 per kg.

## 4. Discussion

Our results indicate significant yield advantages (i.e., TLO and LER) from intercrop plots compared to the sole plots. Higher yield and greater land productivity are possible when non-legume cash crops are intercropped with legumes (Chapagain, 2014; Chapagain and Riseman 2014a, 2014b, 2015; Ghalay et al., 2005; Jahanzad et al., 2015; Kermah et al., 2017; Masvaya et al., 2017; Nwaogu and Muogbo, 2015; Pelzer et al., 2012). 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 in Southern Africa with increased yields (9-48%) and LERs (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 (2014) and Chapagain and Riseman (2014a, 2014b, 2015) demonstrated the 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% 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 the same level of yield. Chen et al. (2004) compared 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 highest improvement in ginger yield and soil chemical attributes when ginger was planted with legumes (e.g., cowpea, soybean, mung-bean and lablab) in 1:2 rows. They further demonstrated that growing ginger:legume in more than 1:2 mixtures decreased rhizome yield of ginger in the Guinea Savanna of Nigeria.

It is important to note that there was a change in total plant number in intercrop plots versus sole plots in 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 higher maize yield in intercrops versus sole crop was due to higher HI (likely due to switch to line sowing and recommended spacing). However, the total plant number decreased in other combinations yet a yield gain (or greater TLO) was observed which may be attributed to a more efficient use of plant resources (i.e., water, light, and nutrients) compared to the sole plots. 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 in 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 including increasing biological diversity, promoting species interaction and enabling natural regulation mechanisms (Hauggaard-Nielsen et al., 2007), reducing soil erosion (Lithourgidis et al., 2011), increasing weed suppression (Bulson et al., 1997; Haymes and Lee, 1999), increasing moisture retention (Ghanbari et al., 2010), maintaining soil fertility through the legume-rhizobia symbiosis (Chapagain, 2014; Hauggaard-Nielsen et al., 2009), increasing nutrient cycling (Chapagain and Riseman, 2014a, 2015; Hauggaard-Nielsen et al., 2003; Jensen, 1996) and biological nitrogen fixation (Bulson et al., 1997; Chapagain and Riseman, 2014a, 2015). This ultimately provides 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 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 the maize; however, shading out of the maize by the companion cowpea might occur when rainfall is plentiful (Shumba et al., 1990). 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, the within-row intercrop pattern could be the productive and lucrative system over inter-row system (Kermah et al., 2017).

Our results of the post-season soil analysis showed that soil P concentrations in both the control plot (i.e. sole crop) and the intercrop plots were higher than the baseline values at both locations, with Kaski site showing higher values than Dhading. Higher values in the intercrop plots could be associated with the addition of nutrients in soil through legume biomass; however, some other possible factors that could affect P level in the sole plots include: topographical variation between two sites – sloppy terrain in Dhading and comparatively flat terraces in Kaski districts, addition of farm yard 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), climatic variation (e.g., rainfall) as well as possible human errors during soil P analysis. It is important to note that the two project sites (Kaski and Dhading) were managed by different staff due to remoteness of sites but they were trained with same protocols.

Overall, the yield advantage and associated potential economic returns with maize + cowpea, millet + soybean, wheat + pea, mustard + pea, and ginger + maize-soybean combinations showed that the crop mixtures was 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 with monoculture that it is a promising option for resource-poor farmers across seasons and soil types in developing countries. 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, 2012; Chapagain, 2014; Chapagain and Riseman 2014a, 2014b, 2015).

possible sources of variation between sites: rainfall, temperature, slope between Dhading and Kaski may have been due to different field staff (day to day management over 12 months and sample collection); different staff due to remoteness of sites but trained with same protocols.

## 5. Summary and Conclusions

Table 9-10 summarize the effects of the treatment, production year and location on the TLO, LER and net potential economic return which help to identify the most productive intercrop combination for maize, millet, mustard, wheat and ginger. As seen in the tables, the followings are appeared as the most productive and economic combinations for different growing seasons in Kaski and Dhading districts of Nepal.

1. Season 1 (March/April to July/August): maize + cowpea var. Makaibodi with an average TLO (4.43 t $ha^{-1}$ i.e., 26% higher than the sole maize) and LER (1.64). This increases farmers' potential income by 64% (i.e., from $1612 to $2640 per season per ha).
2. Season 2 (July/August to November/December): millet + soybean with an average TLO and LER of 2.21 t $ha^{-1}$ (26% higher than the sole millet) and 1.40, respectively. This increases farmers' potential income by 154% (i.e., from $645 to $1632 per season per ha due to higher price of soybean).
3. Season 3 (November/December to March/April): mustard + pea with an average TLO (2.14 t $ha^{-1}$ i.e., 30% higher than the sole mustard) and LER (1.36). This increases farmers' potential income by 12% (i.e., from $3756 to $4220 per season per ha). In the meantime, wheat + pea too 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 increases net potential economic return by 30% (i.e., from $917 to $1196 per season per ha). The total potential economic returns from mustard + pea system were higher compared to the wheat + pea combination due to higher market value of mustard over the wheat.
4. In Kaski, the ginger-based year-round combination appeared to be productive with an average TLO of 22.2 t $ha^{-1}$ (2% higher than the sole ginger) and LER of 2.69 which increased net potential economic return by 11% (i.e., from $12,099 to $13,417 per year per ha). However, the 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.
5. Significant variation was observed between locations (for millet + soybean, mustard + pea combinations) and production years (for millet + soybean and ginger-based year-round system). In general, both sites observed higher yields, TLOs and LERs in year 2 perhaps associated with the higher rainfall compared to year 1. Similarly, higher yields and TLO in Kaski could be associated with higher soil organic matter in Kaski's soils compared to Dhading district.

Above all, intercropping appeared to be a robust option across seasons and soil types confirming that it is a promising practice for resource-poor smallholder farmers in developing countries.

**Table 9:** Average yield, total land output (TLO, grain yield, t $ha^{-1}$), plant population, harvest index (HI, %) and land equivalent ratios (LER) for selected intercrop combinations in 2015-2016 in Dhading and Kaski districts of Nepal.

| Intercrop Combination | Intercrop Plot (t $ha^{-1}$) | | | Control (Non-legume) TLO (t $ha^{-1}$) | Main Crop - Harvest Index (%) | | % Increase in TLO | % Potential Increase in Income# | LER |
|---|---|---|---|---|---|---|---|---|---|
| | Non-legume | Legume | TLO | | Sole | Intercrop | | | |
| Maize + cowpea var. mb | 3.99 (40) | 0.44 (33) | $4.43^{**}$ (73) | 3.52 (56) | 46 | $49^{*}$ | + 26 | + 64 | 1.64 |
| Millet + soybean | 1.65 (564) | 0.56 (48) | $2.21^{**}$ (612) | 1.76 (644) | 29 | $32^{*}$ | + 26 | + 154 | 1.40 |
| Mustard + pea | 1.71 (1413) | 0.43 (42) | $2.14^{ns}$ (1455) | 1.64 (1717) | 25 | $27^{ns}$ | + 30 | + 12 | 1.36 |
| Wheat + pea (Dhading) | 2.49 (4197) | 0.41 (49) | $2.90^{**}$ (4246) | 2.50 (4668) | 45 | $46^{ns}$ | + 16 | + 30 | 1.31 |
| Ginger + maize-soybean (Kaski) | Ginger: 17.02 (42), maize: 4.01 (43), soybean: 1.21 (52) | | $22.2^{ns}$ (137) | 21.9 (69) | 53 | $52^{ns}$ | + 2 | + 11 | 2.69 |

$^{ns}$not-significant; $^{**}$P <0.01 and $^{*}$P <0.05 at 0.05 alpha level;

Figures in parenthesis indicate number of plants in 9 $m^2$ area;

#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: $0.75 per kg, wheat: $0.4 per kg and ginger: $0.6 per kg.

**Table 10:** 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-test.

| 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 | ** | ns | ns | ns | ns |
| 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.

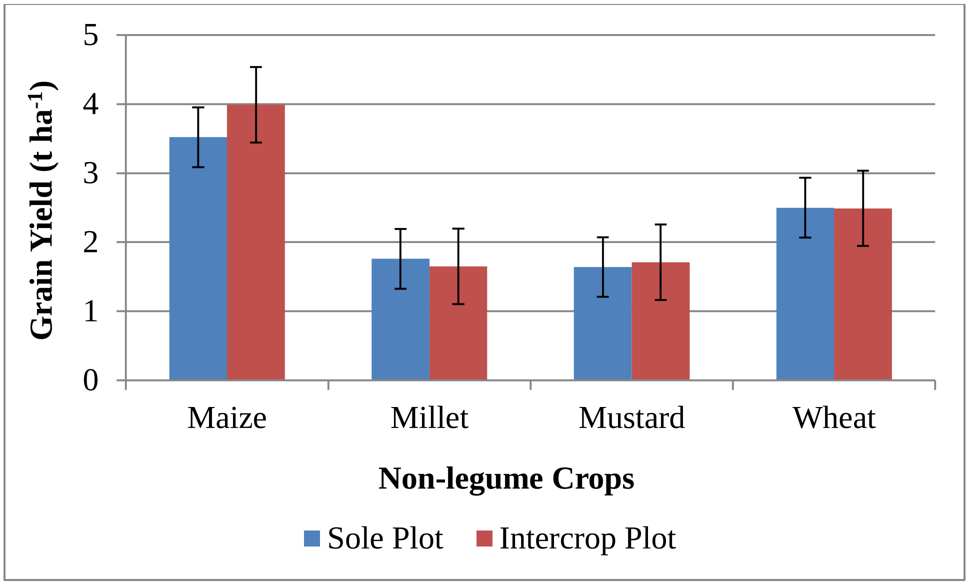



**Figure 3:** Two year average grain yield of non-legume crops (t $ha^{-1}$) from the sole and selected intercrop plots across the two sites (with error bars with standard error).

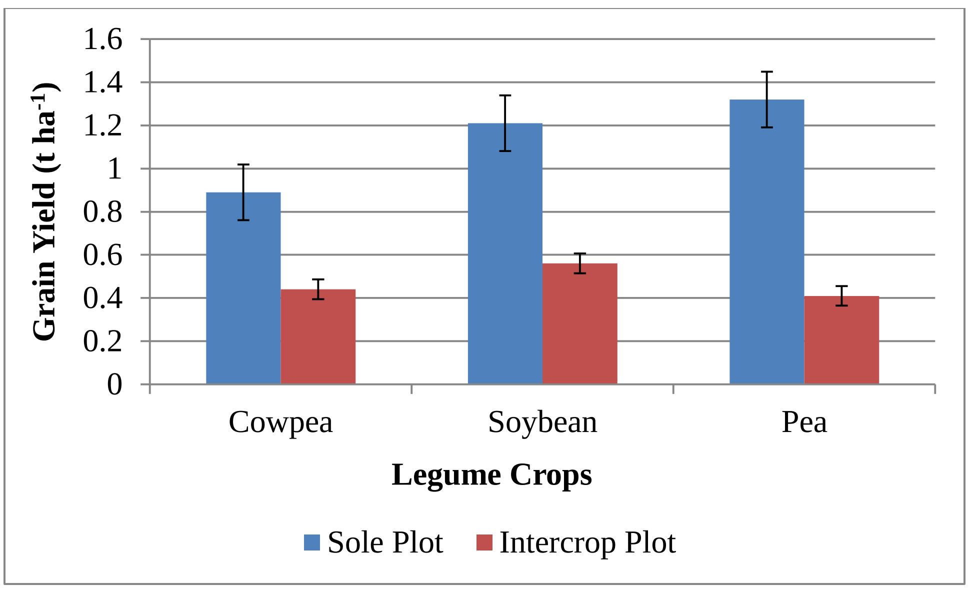



**Figure 4:** Two year average grain yield of legume crops (t $ha^{-1}$) from selected intercrop plots and sole legume plots (additional plots to calculate LER, see Methods) across the two sites (with error bars with standard error).

**List of Abbreviations**

HI – Harvest index

LER – Land equivalent ratios

LI-BIRD – Local initiatives for biodiversity, research and development

masl – meters above sea level

ppm – parts per million

SAKNepal – Sustainable agriculture kits - Nepal

SOM – Soil organic matter

TLO – Total land outputs

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**References**

Anderson, J.M., and J.S.I. Ingram (eds.). 1993. Tropical soil biology and fertility: A handbook of methods. UK: CAB International (ISBN: 0 85198 821 0).

Bulson, H.A.J., R.W. Snaydon, and C.E. Stopes. 1997. Effects of plant density on intercropped wheat and field beans in an organic farming system. *J. Agric. Sci.* 128:59-71.

CBS (Central Bureau of Statistics). 2011. Nepal living standard survey. National Planning Commission Secretariat, p. 6. Kathmandu: Government of Nepal.

Chapagain, T. 2014. Intercropping wheat and barley with nitrogen fixing legume species in low input organic systems [online]. Available: https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0166980 (2016 Dec 08). DOI: 10.14288/1.0166980.

Chapagain, T. 2016. Monoculture and intercropping: Land and ecosystem productivity, nitrogen transformation, and water use efficiency in low input organic systems. Saarbrucken, Germany: LAP LAMBERT Academic Publishing (ISBN: 978-3-659-94767-4).

Chapagain, T., and A. Riseman. 2012. Evaluation of heirloom and commercial cultivars of small grains under low input organic systems. *Am. J. Plant Sci.* 3(5), 655.

Chapagain, T., and A. Riseman. 2014a. Intercropping wheat and beans: Effects on agronomic performance and land productivity. *Crop Sci.* 54(5), 2285-2293.

Chapagain, T., and A. Riseman. 2014b. Barley-pea intercropping: Effects on land productivity, carbon and nitrogen transformations. *Field Crop. Res.* 166, 18-25.

Chapagain, T., and A. Riseman. 2015. Nitrogen and carbon transformations, water use efficiency and ecosystem productivity in monocultures and wheat-bean intercropping systems. *Nutr. Cycl. Agroecosys*. 101(1), 107-121.

Chapagain, T., and G.B. Gurung. 2010. Effects of integrated plant nutrition management (IPNM) practices on the sustainability of maize based hill farming systems in Nepal. *J. Agric. Sci.* 2(3), 1-7.

Chapagain, T., and M.N. Raizada. 2017a. Agronomic challenges and opportunities for smallholder terrace agriculture in developing countries. *Front. Plant Sci.* 8: 331.

Chapagain, T., and M.N. Raizada. 2017b. Impacts of natural disaster on smallholder farmers: gaps and recommendations. *Agric. Food Sec.* 6(1): 39.

Chen, C., M. Westcott, K. Neill, D. Wichman, and M. Knox. 2004. Row configuration and nitrogen application for barley-pea intercropping in Montana. *Agron. J.* 96:1730- 1738.

Ghaley, B.B., H. Hauggaard-Nielsen, H. Hogh-Jensen, and E.S. Jensen. 2005. Intercropping of wheat and pea as influenced by nitrogen fertilization. *Nutr. Cycl. Agroecosys.* 73:201-212.

Ghanbari, A., M. Dahmardeh, B.A. Siahsar, and M. Ramroudi. 2010. Effect of maize (Zea mays L.) - cowpea (Vigna unguiculata L.) intercropping on light distribution, soil temperature and soil moisture in arid environment. *J. Food Agric. Environ.* 8:102-108.

Hauggaard-Nielsen, H., B. Jornsgaard, J. Kinane, and E.S. Jensen. 2007. Grain legume-cereal intercropping: The practical application of diversity, competition and facilitation in arable and organic cropping systems. *Renew. Agr. Food Syst.* 23(1):3-12.

Hauggaard-Nielsen, H., M. Gooding, P. Ambus, G. Corre-Hellou, Y. Crozat, C. Dahlmann, A. Dibet, P. von Fragstein, A. Pristeri, M. Monti, and E.S. Jensen. 2009. Pea-barley intercropping for efficient symbiotic $N_2$-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. *Field Crop Res.* 113(1):64-71.

Hauggaard-Nielsen, H., P. Ambus, and E.S. Jensen. 2003. The comparison of nitrogen use and leaching in sole cropped versus intercropped pea and barley. *Nutr. Cycl. Agroecosys.* 65:289-300.

Haymes, R., and H.C. Lee. 1999. Competition between autumn and spring planted grain intercrops of wheat (*Triticum aestivum*) and field bean (*Vicia faba*). *Field Crop Res.* 62(2-3):167-176.

Inal, A., A. Gunes, F. Zhang, and I. Cacmak. 2007. Peanut/maize inter-cropping induced changes in rhizosphere and nutrient concentrations in shoots. *Plant Physiol. Biochem.* 45:350-356.

Jahanzad, E., A. Sadeghpour, M.B. Hoseini, A.V. Barker, M. Hashemi, and R.K. Afshar. 2015. Competition, Nitrogen Use Efficiency, and Productivity of Millet–Soybean Intercropping in Semiarid Conditions. *Crop Sci.* 55: 2842-2851.

Jensen, E.S. 1996. Grain yield, symbiotic $N_2$ fixation and interspecific competition for inorganic N in pea-barley intercrops. *Plant Soil* 18:25-38.

Jeranyama, P., O.B. Hesterman, S.R. Waddington, and R.R. Harwood. 2000. Relay intercropping of Sunnhemp and Cowpea into a smallholder maize system in Zimbabwe. Agron. J. 92: 239-244.

Jolliffe, P.A., and F.M. Wanjau. 1999. Competition and productivity in crop mixtures: some properties of productive intercrops. *J. Agric. Sci.* 132:425-435.

Kermah, M., A.C. Franke, S. Adjei-Nsiah, B.D.K. Ahiabor, R.C. Abaidoo, and K.E. Giller. 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. *Field Crop Res.* 213: 38-50.

Li, L., D. Tilman, H. Lambers, and F.S. Zhang. 2014. Plant diversity and overyielding: Insights from belowground facilitation of intercropping in agriculture. *New Phytol.* 203: 63-69.

Lithourgidis, A.S., C.A. Dordas, C.A. Damalas, and D.N. Vlachostergios. 2011. Annual intercrops: an alternative pathway for sustainable agriculture. *Aust. J. Crop Sci.* 5(4):396-410.

Masvaya, E.N., J. Nyamangara, K. Descheemaeker, and K.E. Giller. 2017. Is maize-cowpea intercropping a viable option for smallholder farms in the risky environments of semi-arid southern Africa? *Field Crop Res.* 209: 73-87.

Mead, R., and R.W. Willey. 1980. The concept of "land equivalent ratio" and advantages in yields from intercropping. *Exp. Agric.* 16: 217-228.

Nwaogu, E.N., and P.C. Muogbo. 2015. Effect of ginger- grain legume cropping system and spatial arrangement on soil fertility management and yield of intercropped ginger in the guinea savanna of Nigeria. *Intl. Res. J. Agric. Sci. Soil Sci.* 5(1): 1-7.

Ofori, F., and W.R. Stern. 1987. Cereal-legume intercropping system. Adv. Agron. 41: 41-90.

Pelzer, E., M. Bazot, D. Makowski, G. Corre-Hellou, C. Naudin, M. Al Rifaï, E. Baranger, L. Bedoussac, V. Biarnès, P. Boucheny, B. Carrouée, D. Dorvillez, D. Foissy, B. Gaillard, L. Guichard, M.C. Mansard, B. Omon, L. Prieur, and M.H. Jeuffroy. 2012. Pea–wheat intercrops in low-input conditions combine high economic performances and low environmental impacts. *European J. Agron.* 40: 39-53.

Riley, K.W., N. Mateo, G.C. Hawtin, and R. Yadav. 1990. Mountain agriculture and crop genetic resources (eds.). Proceeding of international workshop on mountain agriculture and crop genetic resources, Feb 16-19, 1987, Kathmandu. HMG Nepal, International Development Research Centre (IDRC), and International Centre for Integrated Mountain Development (ICIMOD). p. 329. New Delhi: Oxford and IBH Publishing Co. Pvt. Ltd.

Sahota, T., and S. Malhi. 2012. Intercropping barley with pea for agronomic and economic considerations in northern Ontario. *Agric. Sci.* 3:889-895.

Sharma, K.P., K.R. Dahal, and K.R. Neupane. 2001. Introduction to agronomy. pp. 125-136. Rampur, Nepal: Department of Agronomy, Institute of Agriculture and Animal Science.

Shumba, E. M., H.H. Dhliwayo, and O.Z. Mutoko. 1990. The potential of maize-cowpea intercropping in low rainfall areas of Zimbabwe. *Zimbabwe J. Agric. Res.* 28: 33-38.

Subedi, K.D. 1997. Wheat intercropped with tori (*Brassica campestris* var. *toria*) and pea (*Pisum sativum*) in the subsistence farming system of the Nepalese hills. *J. Agric. Sci.* 128(3):283-289.

Thurston, D. 1996. Slash/mulch systems: Sustainable methods for tropical agriculture. Westview Press, Boulder, CO, USA.

Trenbath, B.R. 1974. Biomass productivity of mixtures. *Adv. Agron.* 26:177-210.

Vandemeer, J. 1989. The ecology of intercropping. p. 237. UK: Cambridge University Press (ISBN: 0 521 34592 8).

Wymann von Dach, S., R. Romeo, A. Vita, M. Wurzinger, and T. Kohler (eds). 2013. Mountain farming is family farming: A contribution from mountain areas to the International Year of Family Farming 2014. p. 38, 102. Rome, Italy: FAO, CDE, BOKU.