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Intercropping Maize With Legumes for Sustainable Highland Maize Production

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Residue burning to prepare soil for maize growing deprives the soil of both protective cover and organic matter, and it exacerbates environmental issues such as Southeast Asia's haze problem. This paper reports on a study that evaluated the effectiveness of maize/legume intercropping as an alternative to maize cultivation with residue burning. Cowpea (Vigna unguiculata)*, mung bean* (V. radiata)*, rice bean* (V. umbellata)*, and lablab* (Lablab purpureus) *were sown into a standing maize crop 30 days before harvest, and the results were compared with a maize crop grown using residue burning as the method for land preparation at Pang Da Agricultural Station in Chiang Mai, Thailand, in a replicated trial conducted over 3 growing seasons from 2012 to 2014. Intercropping increased maize grain yield by 31–53% and left 70–170% more residue containing 113–230% more nitrogen than the maize sown after residue burning, depending on the legume, and decreased weed dry weight by two-thirds after 2 seasons. Soil biodiversity was enriched by the intercrops, with a doubling in the spore density of arbuscular mycorrhizal fungi in the root-zone soil and increased abundance, diversity (Shannon index), and richness of the soil macrofauna. The abundance of soil animals increased with crop residue dry weight* ($r = 0.90$, $P < 0.05$) *and nitrogen content* ($r = 0.98$, $P < 0.01$)*. The effect of intercropping on maize grain yield and accumulation of residue and nitrogen were then confirmed in a participatory experiment involving farmers in 2 highland villages in the Phrao and Chiang Dao districts of Chiang Mai Province with maize and rice bean in 2015. The effects of maize/legume intercropping—increased nitrogen accumulation and crop residue, enhanced soil biodiversity, suppression of weeds, and protection of the soil surface, which enabled the maize to be sown without land clearing with fire—should all contribute to sustainable highland maize production.*

Keywords: *Earthworms; intercrop; legume; maize; residue burning; soil macrofauna; Thailand.*

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Introduction

Slash-and-burn agriculture, a traditional practice in the mountains of Southeast Asia, was once the main method for producing the opium cash crop as well as subsistence crops (Kunstadter et al 1978; Mertz et al 2009). The system was productive and sustainable when there was sufficient land to allow plant nutrients to accumulate and weeds and pests to be suppressed by regenerating natural vegetation (Kunstadter 1978; Nakano 1978; Yimyam et al 2003). However, the long duration of fallow is increasingly impossible because of the scarcity of available land and strict implementation of government conservation policies (eg Cramb et al 2009; Fox et al 2009). Maize is one of the few economically viable options for farmers in remote areas who are unable to take advantage of market demand for high-value but perishable cool-weather vegetables. However, maize in the highlands is grown by first cutting down existing vegetation in the field and burning it before sowing. This is different from maize production in the lowlands—where land is ploughed to prepare it for sowing—and is problematic in a number of ways. The burning of residues deprives the soil of protection from the elements, including heavy monsoon rains, as well as organic matter and nutrients. It also contributes to haze and very high concentrations of atmospheric particulate matter, which peaked at more than 4 times the safety standard of 120 μg PM10 (particulate matter diameter that is 10 μm or smaller and thus inhalable) per cubic meter in March and April 2012 in Chiang Rai, Chiang Mai, and Nan (Pollution Control Department 2017), highland provinces at the center of maize production with residue burning in the mountainous region of mainland Southeast Asia as well as within Thailand.

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Intercropping is an ancient practice that remains the dominant form of agriculture in many parts of the world (Brooker et al 2015). Maize/legume intercrops are among the most common and efficient in resource utilization (Okigbo and Greenland 1976; Beets 1982; Francis 1986; Ofori and Stern 1987). Legumes can thrive without soil and fertilizer nitrogen (N) when well nodulated with appropriate N-fixing bacteria. Rice bean (*Vigna umbellata*), cowpea (*V. unguiculata*), lablab (*Lablab purpureus*), and mung bean (*V. radiata*) are common grain legumes in northern Thailand (Rerkasem and Rerkasem 1987). The local legume varieties with indeterminate growth habit, which continue to accumulate dry matter through new vegetative shoots after flowering, are well nodulated with native nodule bacteria and accumulate substantial amounts of N and biomass when grown in the highlands. In farmers' fields in Mae Hong Son, rice bean and lablab reportedly produced 10–11 tonnes per hectare of biomass containing 200–300 kg N per hectare in the off season between the annual rice crops (Chaiwong et al 2012).

This paper reports on 2 experiments: (1) a field experiment to evaluate intercropping maize with rice bean, cowpea, lablab, and mung bean as an alternative to maize cultivation with residue burning as well as the impact of intercropping on biodiversity in the soil; and (2) a participatory experiment comparing the performance of intercropped maize and rice bean with maize sown after residue burning grown by the same farmers.

Material and methods

Study sites

A replicated field experiment (Experiment 1) was conducted at the Royal Pang Da Agricultural Station in Chiang Mai (18.69°N, 99.49° E, elevation 700 m), and a participatory experiment (Experiment 2) was conducted at 2 highland villages in Chiang Mai—Pang Daeng Nai in Chiang Dao district and Loeng Khod in Phrao district (Figure 1). The experimental sites are described in Table 1.

Crop cultivation, sampling, and analysis

Experiment 1 compared traditional highlands maize sown after residue burning with maize/legume intercropping. In total, 5 plots were planted at Pang Da—1 with maize alone, after the plot was prepared by burning the previous crop's residue and the other 4 with maize intercropped with rice bean, cowpea, mung bean, and lablab, respectively. Planting took place in May at a spacing of 0.50 × 0.75 with 2 plants per hill in a field with an 8% slope. Each plot was 5 × 6 m with a 0.5 m wide alley between plots. Plots were arranged in a completely randomized block design with 3 replicates (each block 5 × 33 m); together, they covered an area of 500 m^2.

To grow maize after residue burning, farmers generally use one of many available maize hybrids and a moderate level of N fertilizer at 80–100 kg N per hectare. This experiment used the seed of maize hybrid CP888; a basal fertilizer treatment that included 72 kg N per hectare (as urea) was applied to all 5 cropping systems 1 month after sowing, followed by 25 kg N and 14 kg phosphorus (P) (as ammonium phosphate) per hectare 1 month later. In the intercropped plots, the maize was treated in the same way and received the same fertilizer treatment as the maize sown after residue burning; 1 month before the maize harvest, the seeds of locally available legumes were sown between the rows of maize at the rate of 50 kg per hectare, and grown without additional fertilizer. The experiment took place over 3 growing seasons from 2012 to 2014.

In 2014, the dry weight of weeds was determined from a 1 × 1 m quadrat within each plot before maize planting. Grain yield and the dry weight of the residue of maize and legumes were recorded at maturity of each crop. The legumes matured and were harvested for grain at different times: mung bean in mid-November (75 days after sowing), cowpea in December (100 days), rice bean in January (120 days), and lablab in March (180 days). From each plot, grain yield and dry weight were collected from an internal area of 2.25 m^2 for maize and 1 m^2 for each of the legumes. Samples were dried at 75°C for 72 hours. Grain yield was expressed at 14% moisture content. The dried maize and legume samples were ground and analyzed for Kjeldahl N.

Experiment 2 was a participatory experiment comparing the feasibility of maize/rice bean intercropped under farmer's management with that of maize sown after residue burning. It involved 3 farmers in 2 villages—Pang Daeng Nai, where rice bean was a common cash crop, and Loeng Khod, where it was not. The plot size of each cropping system in each farmer's field was approximately 20 × 20 m; 1 farmer's field was treated as 1 replicate. Crop management was similar to that used in Experiment 1, except that fertilizer was applied to both the intercrop and maize sown after residue burning according to the farmer's normal practice, ranging from 30 to 70 kg N per hectare and from 0 to 11 kg P per hectare. Grain yield, residue dry weight, and N content were determined as in Experiment 1.

Sampling for macrofauna and arbuscular mycorrhizal fungi

Samples were taken at maize flowering in 2014. Soil macrofauna, animals larger than 2 mm, were collected from a 0.25 × 0.25 m section of surface soil in the area between the maize plants to 0.25 m depth inside each plot. The samples were sorted by hand, identified using a key for soil invertebrates (Julka 2016), and the number of individuals determined. Identification of species was not possible in most cases, and so organisms were identified in

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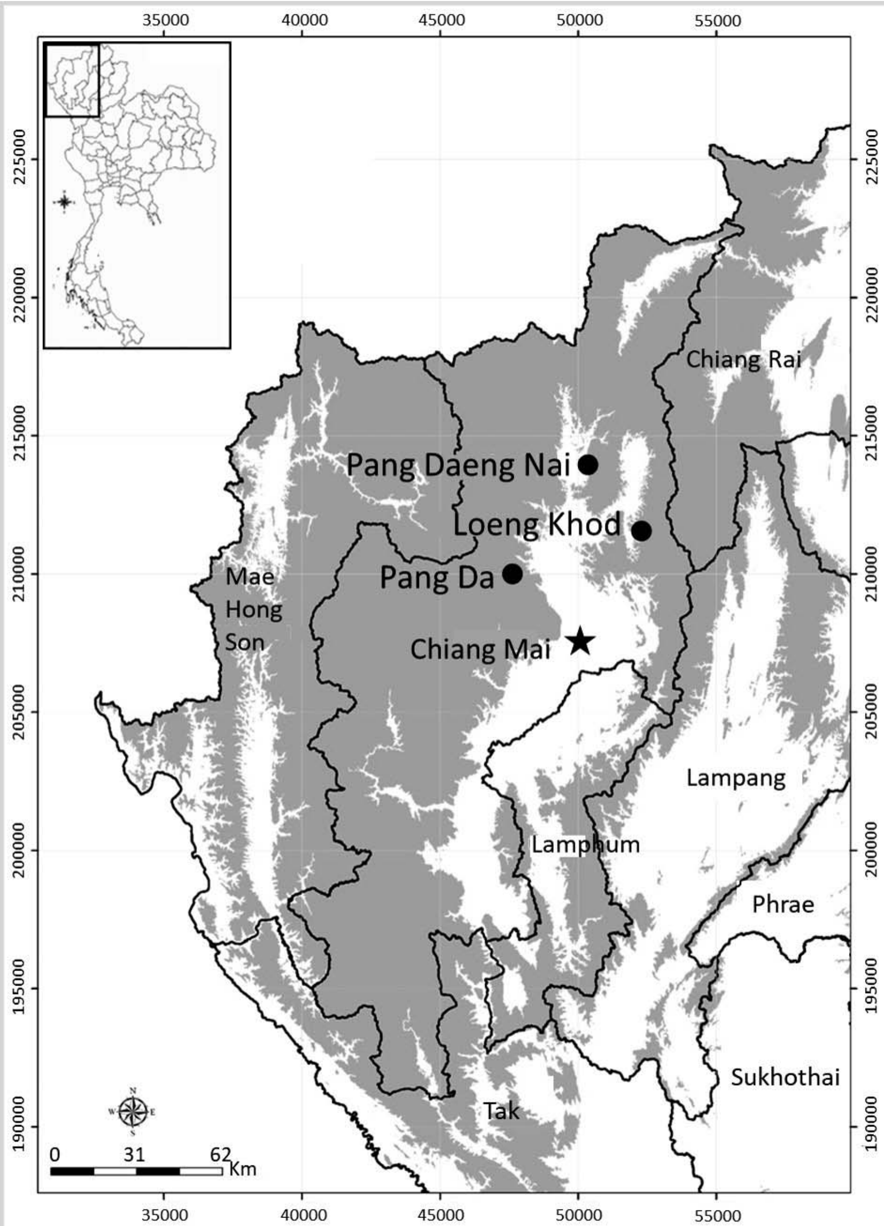
FIGURE 1 Locations of experiments in the highlands of northern Thailand: Pang Da (Experiment 1); Pang Daeng Nai and Loeng Khod (Experiment 2). Shaded areas indicate the highlands; internal lines indicate provincial borders. (Map by B. Rerkasem)



terms of major species groups (eg ants, beetles, and centipedes). Richness was represented as the number of these groups occurring within a sample. The Shannon diversity index (H') was determined as follows:

$$H' = -\sum_{i=1}^{s} pi \ln pi \qquad (1)$$

where $s =$ the number of major species groups and $pi =$ the relative abundance of each species group (Power and McSorley 2000; Coffey 2002).

The abundance of arbuscular mycorrhizal (AM) fungi was estimated based on the number of fungi spores, determined by wet sieving and 50% sucrose centrifugation (Brundrett et al 1996). Briefly, a 20-g soil subsample from the root zone was taken from inside each plot (a composite of 5 random samples taken from 0–25 cm depth from the area between the maize plants) and rinsed repeatedly with tap water through 50–750 μm sieves to separate the spores from soil particles and roots. The result of the final sieving was suspended in water and centrifuged for 5 minutes at 2000 rpm; floating debris and

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TABLE 1 Description of experimental sites.

	Experiment 1	Experiment 2	
	Pang Da	Pang Daeng Nai	Loeng Khod
Latitude, longitude	18.86° N, 98.76° E	19.35° N, 99.02° E	19.14° N, 99.21° E
Elevation (m above sea level)	700	500	550
Slope (%)	8%	27%	23%
Annual rain (mm)	1238	1156	1145
Temperature average (°C)	23.2	26.3	23.0
Temperature range (°C)	(12.8–35.8)	(19.2–33.4)	(14.3–36.1)
Soil type	Sandy clay loam	Sandy clay loam	Sandy clay loam
Soil pH	5.8 ± 0.2	5.7 ± 0.2	5.0 ± 0.1
Organic matter (%)	3.1 ± 0.1	2.9 ± 0.2	3.9 ± 0.2
Phosphorus, available (ppm)[a)]	1.9 ± 0.3	7.2 ± 0.7	2.4 ± 0.7
Potassium, extractable (ppm)	268 ± 44	201 ± 59	204 ± 18

[a)] Bray II test.

supernatant were discarded. After resuspension in 50% sucrose, the soil was centrifuged for 1 minute at 2000 rpm. The supernatant was washed on a 50-μm sieve to remove sucrose and filtrated by vacuum. The spores on the filter paper were counted, and the result was expressed on a per gram dry soil basis.

Statistical analysis

Statistix version 8 was used in data analysis for analysis of variance, with least significant difference ($P < 0.05$) for comparing intercrops with maize sown after residue burning and for comparing pairs of intercrops. Significance of the correlation coefficient was determined by analysis of variance of the linear regression coefficient.

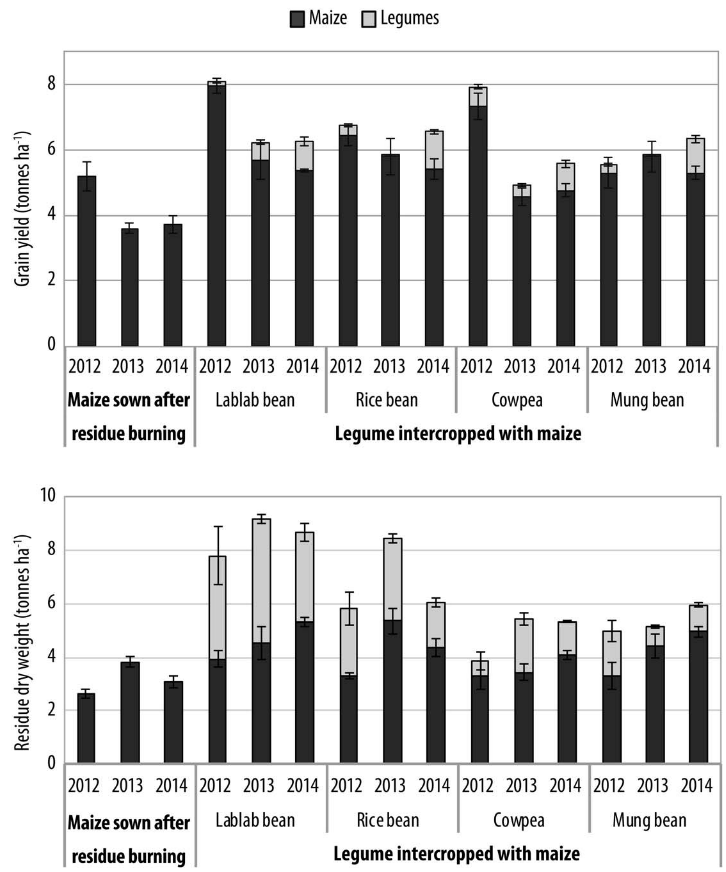
Results

Grain yield and crop residue dry weight of the maize/legume intercrops were significantly higher ($P < 0.001$) than those from the maize sown after residue burning (Figure 2). Over the 3 years of the experiment, grain yield of intercropped maize averaged 53% higher than that of maize sown after residue burning when the legume was lablab and 33% higher with rice bean, cowpea, and mung bean. Year-to-year variation in grain yield was much larger in the legumes than in maize. The coefficient of variation of the maize yield ranged from 3% in maize/mung bean to 16% in maize/cowpea; for legume grain yield, it was 19% for cowpea, 46% for lablab, 66% for rice bean, and 68% for mung bean. A particularly poor year for the legumes was 2013, when grain yield of rice bean and mung bean was virtually nil; cowpea and lablab yielded only 0.4–0.5 tonnes per hectare.

More residue accumulated under the intercrops than under the maize sown after residue burning, ranging from 20% more under maize/cowpea to 33% under maize/mung bean, 57% under maize/rice bean, and 105% under maize/lablab. After 2 growing seasons, the weed biomass in the intercrops averaged 0.39 ± 0.04 tonnes per hectare, compared with 1.17 ± 0.13 tonnes per hectare in the maize sown after residue burning (Figure 3). In 2014, the higher N content of intercropped maize, together with the N from legumes, contributed to significantly more aboveground N in the intercrops than in the maize sown after residue burning ($P < 0.05$) (Figure 4). Nitrogen removed in the harvested grains of the intercrops was twice that in the maize sown after residue burning. In the crop residue there was 6 times as much N in maize/lablab and 3 times as much in maize/rice bean, maize/cowpea, and maize/mung bean as in the maize sown after residue burning.

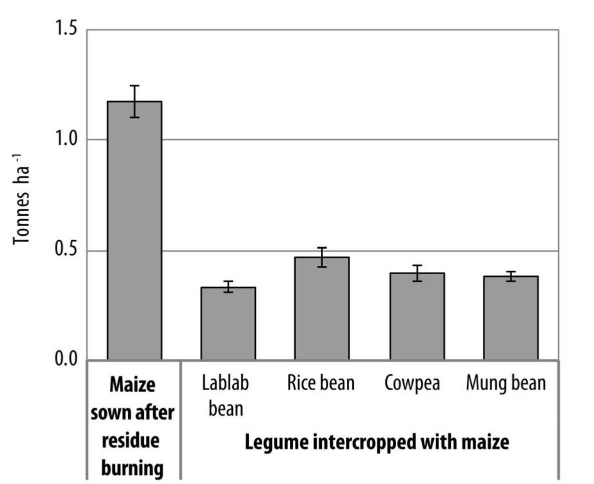
Soil biodiversity, determined at the time of maize flowering in the third season of cropping (2014), was enhanced by the maize/legume intercrops, with the abundance of soil animals closely correlated with crop and residue dry weight and N contents (Table 2). The Shannon diversity index was 1.67 in maize/lablab and maize/mung bean, 2.04 in maize/cowpea, and 2.08 in maize/rice bean, compared with 1.29 in the maize sown after residue burning. Abundance and richness of the soil macrofauna increased under maize/legume intercrops. The number of individual soil animals was 80 m^{-2} in maize sown after residue burning and 3 to 5 times as high in the intercrops. The number of earthworms and total number of soil animals correlated significantly with crop and residue dry weight and their N content, but the

FIGURE 2 Grain yield and residue dry weight (± standard error bars) of maize/legume intercrops compared with maize sown after residue burning for the 2012, 2013, and 2014 growing seasons (Experiment 1).



		Significance by analysis of variance			$LSD_{0.05}$
		Cropping system (CS)	Year	CS × year	
Grain yield	Maize	$p < 0.001$	$p < 0.001$	$p < 0.001$	0.82
	Legume	$p < 0.05$	$p < 0.001$	$p < 0.001$	0.19
Residue	Maize	$p < 0.001$	$p < 0.001$	$p < 0.05$	0.79
	Legume	$p < 0.001$	$p < 0.001$	$p < 0.001$	1.13

FIGURE 3 Weed dry weight (± standard error bars) from maize/legume intercrops compared with maize sown after residue burning at the beginning of the 2014 growing season (Experiment 1). Effect of cropping system by analysis of variance significant at $P < 0.05$ ($LSD_{0.05}$ 0.15).



associations with the number of insects and other arthropods were not significant. Root-zone soil contained twice as many AM fungi spores in the intercrops as in the maize sown after residue burning. Only 3 soil animal species groups were found in maize sown after residue burning: earthworms, which accounted for 74% of the individual animals, ants, and springtails. In contrast, 6–9 animal species groups were found in the intercrops (Table 3). Earthworms were also the dominant soil animal in the maize/legume intercrops, accounting for 64–84% of the individual animals. Some animals were unique to specific intercrop legumes. For example, pygmy grasshopper and ground beetle were present only in maize/lablab; earwig, termite, and true bug in maize/rice bean, and beetle and leafhopper were present only in maize/cowpea.

The effect of intercropping in increasing grain yield, residue dry weight, and N content was confirmed in the fields of farmers participating in Experiment 2 (Table 4). In addition to a maize grain yield that was higher than the yield for maize sown after residue burning (by 18% at Pang Daeng Nai and 33% at Loeng Khod), the maize/rice bean intercrop also produced 1.3–1.4 tonnes per hectare of rice bean grain. The intercrop rice bean added 3.1 tonnes per hectare to the residue at Pang Daeng Nai and

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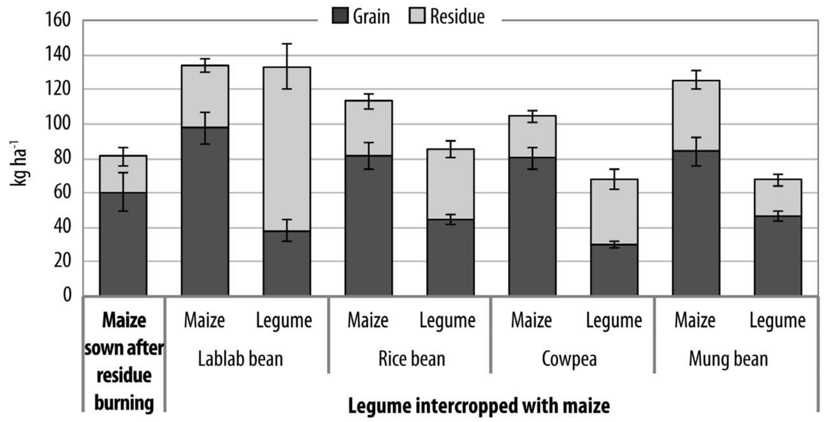
FIGURE 4 Grain and residue N (± standard error bars) in maize/legume intercrops compared with maize sown after residue burning for 2014 growing season (Experiment 1). Effect of cropping system by analysis of variance significant at $P < 0.05$.



		$LSD_{0.05}$
Grain N	Maize	18.9
	Legume	9.3
Residue N	Maize	13.6
	Legume	25.0
Total intercrop aboveground N		33.9

TABLE 2 Diversity, richness, and abundance of soil macrofauna and abundance of arbuscular mycorrhizal fungi in maize sown after residue burning and maize/legume intercrops (to 0.25 m depth) during maize flowering in the 2014 cropping season as well as correlations between the abundance of soil animals and crop and residue dry weight and N content (Experiment 1).

	Maize sown after residue burning	Maize intercrop with			
		Lablab	Rice bean	Cowpea	Mung bean
Macrofauna diversity and richness[a)]					
Shannon diversity index	1.29x	1.67y	2.08z	2.04z	1.67y
Richness[b)]	3.00a	6.00b	9.00z	9.00z	8.00z
Abundance of macrofauna groups (individual animals m^{-2})[a)]					
Insects	21.30x	53.30y	64.00y	69.30y	21.30x
Other arthropods	0.00	10.70	42.70	10.70	26.70
Earthworms	58.70x	341.70z	186.70y	192.00y	250.70xy
Total	80.00x	378.70y	293.30y	272.00y	298.70y
Arbuscular mycorrhizal fungi in the root zone[a),b)]					
Spores g^{-1} soil	2.70x	5.30y	5.30y	6.20y	5.60y
	Correlation coefficient (r)				
	Earthworms	Insects	Other arthropods		Total
Residue dry weight	0.88*	0.45 NS	0.34 NS		0.90*
Residue nitrogen	0.91*	0.47 NS	0.19 NS		0.90*
Crop dry weight	0.92*	0.53 NS	0.37 NS		0.95*
Crop nitrogen	0.96**	0.47 NS	0.40 NS		0.98**

a) Different letters designate a least significant difference of 0.05.

b) Number of major species groups. For the purposes of this study, organisms were quantified in broad categories (eg ants, beetles, and centipedes) rather than by species.

* Significant at $P < 0.05$; ** significant at $P < 0.01$; NS indicates not significant at $P < 0.05$.

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TABLE 3 Macrofauna present in the soil under maize sown after residue burning and maize/legume intercrop during 2014 cropping season (Experiment 1).

Macrofauna (taxonomic identity)	Maize sown after residue burning	Maize intercrop with			
		Lablab	Rice bean	Cowpea	Mung bean
Ant (Formicidae, family)	+	+	+	+	
Beetle (Coleoptera, order)				+	
Centipede (Chilopoda, class)			+	+	+
Cricket (Gryllidae, family)				+	
Earthworm (Oligochaeta, class)	+	+	+	+	+
Earwigs (Dermaptera, order)			+		
Ground beetle (Carabidae, family)		+			
Leafhopper (Cicadellidae, family)				+	
Millipede (Diplopoda, class)			+		+
Moth pupa (Lepidoptera, order)			+		+
Pygmy grasshopper (Tetrigidae, family)		+			
Scarab beetle (*Scarabaeus sacer*, species)		+	+	+	+
Soldier fly pupa (*Hermetia illucens*, species)					+
Springtail (Collembola, subclass)	+			+	+
Termite (Termitoidae, epifamily)			+		
True bug (Hemiptera, order)			+		
Whip scorpion (Thelyphonida, order)		+		+	+

3.6 tonnes per hectare at Loeng Khod, bringing total intercrop residue to 5.5–6.4 tonnes per hectare, compared with 1.7–2.7 tonnes per hectare of residue from maize sown after residue burning. The aboveground part of the maize/rice bean intercrop contained 3 times as much N as the maize sown after residue burning, and the residue N of the intercrop was 5–6 times that of the maize sown after residue burning.

Discussion

The general benefit of cereal/legume intercrops in better resource utilization has been discussed in many reviews (eg Beets 1982; Ofori and Stern 1987). The advantages of maize/legume intercrops have been demonstrated in many studies in Thailand (eg Rerkasem and Rerkasem 1988; Devkota and Rerkasem 2000; Polthanee and Trelo-ges 2003), and the cultivation of maize/legume intercrops involving local varieties of rice bean, lablab, and cowpea by farmers in the mountains of northern Thailand has been described (Ongprasert and Prinz 2004). With locally available grain legumes, the intercrop advantages demonstrated here included higher yield of the harvested grains and larger amounts of N-rich residue to protect the soil surface from the elements, contribute to the soil organic matter pool, and enhance soil fertility. The mulching effect of the much greater volume of residue from the intercrops suppressed weeds, enabled the maize to be sown without tillage, and eliminated the need to clear the soil surface by burning, which is essential with the much smaller volume of residue from maize alone.

In addition, the residue mulch protects the soil surface against erosion, especially when crops are planted on steep slopes (Lal et al 2007), which is often the case for maize in the highlands. In a soil erosion study, intercropping of maize and lablab was shown to effectively increase rainfall infiltration and lessen surface runoff and loss of soil and nutrients by erosion on 33–48% of slopes by the second year (Punyalue et al 2016). Resistance to rainfall penetration in similar highland soil was shown to be significantly reduced by hoeing, which broke up the soil surface (Ziegler et al 2000). The effect of the soil surface opening for legume sowing in improved rainfall infiltration and lessening of surface runoff offers one possible explanation of the often higher grain yield of intercrop maize over maize sown after residue burning in the short run. Improvement in soil physical properties from the buildup of soil organic matter and activities of

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TABLE 4 Grain yield, crop residue, and N content of maize sown after residue burning and maize/rice bean intercrop in 2 highland villages (Experiment 2).

Village	Pang Daeng Nai		Loeng Khod	
Cropping system[a)]	Maize sown after residue burning	Maize/rice bean intercrop	Maize sown after residue burning	Maize/rice bean intercrop
Grain yield (mg per hectare)				
Maize	3.3x	3.9y	2.4x	3.2y
Rice bean	0.0	1.3	0.0	1.4
Crop residue (dry weight, mg per hectare)				
Maize	1.7	2.4	2.7	2.8
Rice bean	0.0	3.1	0.0	3.6
Total	1.7x	5.5z	2.7y	6.4z
Grain nitrogen (kg per hectare)				
Maize	52.7	66.9	39.1	52.8
Rice bean	0.0	44.0	0.0	49.8
Total	52.7x	110.9y	39.1x	102.6y
Residue nitrogen (kg per hectare)				
Maize	13.8	17.7	19.3	25.2
Rice bean	0.0	62.0	0.0	66.3
Total	13.8x	79.7y	19.3x	91.5y
Cropping system aboveground nitrogen (kg per hectare)				
Total	66.5x	190.6y	58.4x	194.1y

[a)] Different letters designate significant difference between cropping systems at each location by a least significant difference of 0.05.

soil animals under the maize/legume intercrop should contribute to similar effects in the long run.

In addition to the physical protective mulching effect, the maize/legume intercrops were also shown to enhance soil biodiversity, with greater Shannon diversity index, abundance and richness of soil animals, and density of AM fungi spores in the intercrops than in the maize sown after residue burning. Annual cropping has been reported to be associated with the lowest diversity and abundance of soil macrofauna as well as soil organic matter in different types of land use, including natural forests, tree crops, and pasture (Lavelle et al 1994). While the soil populations supported by multiple cropping systems are much more diverse than those under monoculture, it has been pointed out that community structure is more strongly influenced by quantity and quality of the organic matter than diversity of the plants (Thiele-Brunh et al 2012). This was confirmed in the present study with the close positive correlation between the dry weight and N content of the residue and the abundance of soil animals and earthworms. However, a degree of specificity between each type/species of soil animal and legume species is suggested by the different soil animal species groups associated with different legumes found here. A closer examination of the ecological functions of the animals should be useful in identifying the intercrop legumes' potential to promote beneficial insects or harbor insect pests.

Crop production benefits from soil biodiversity through the improvement of soil fertility by activities of the soil population. The interconnected roles of soil biodiversity and organic matter in the maintenance of soil fertility and sustainability of crop production are well recognized, as explicitly stated in the World Soil Charter (FAO 2015). The availability of essential nutrients is increased and the soil's physical attributes are improved by the ingesting and digesting as well as tunneling activities of soil animals (Lavelle et al 1994). AM fungi are obligate symbionts that function through extensive external hyphal networks that enhance the uptake of nutrients (especially P) and water by plant roots (Harley and Smith 1983).

The abundance of AM fungi spores, which function as propagules in the symbiotic development, vary with the vegetation and management practices (Gavito and Miller 1998; Boddington and Dodd 2000). Development of the

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AM fungi is affected more strongly by some plants than others. In maize, the AM fungi association that develops early in the crop growth can contribute significantly to the crop's acquisition of P (Miller 2000). As maize has been reported to produce significantly fewer spores than other common field crops in the highlands, including legumes (Wongmo et al 2008; Kongpan 2010), the stimulating effect of intercrop legumes in the production of the AM spores should be beneficial to maize yield.

Crop production in the mountains of Southeast Asia has evolved from largely subsistence-oriented to commercial (Rerkasem 2005), and the primary role of economic incentive in the choice of cropping systems in the highlands of Thailand has been confirmed by many (eg Polthanee and Trelo-ges 2003; Ongprasert and Prinz 2004; Yap et al 2016). The economic advantage from the legume grain yield, therefore, needs to be considered in view of possible yield instability by season and location. The rice bean grain yield of 1.3–1.4 tonnes per hectare in farmers' fields in Experiment 2 of this study is comparable to other findings: 0.9 to 1.6 tonnes per hectare experimental yield of rice bean (Rerkasem and Rerkasem 1988), and farmers' regular crop yield of 0.6–1.5 tonnes per hectare at Pang Daeng Nai (Royal Project database, unpublished, accessible through first author of this article).

However, compared with these, and with yields of 0.7–0.9 tonnes per hectare for mung bean (OAE 2015) and cowpea (Polthanee and Wannapat 2000), legume grain yield from the intercrops in some years and locations (eg 2013 in Experiment 1) would be too low to cover even the cost of harvesting. However, while the importance of short-term economic incentives to highland farmers' choice of cropping system is not to be disregarded, the maize/legume intercrops were shown to provide other services—such as eliminating the need for land preparation by burning—with the potential to contribute to sustainability of highland maize production in the long run.

Legumes, which can thrive without soil and fertilizer N when well nodulated with appropriate N-fixing bacteria, are stimulated to derive more of their N supply from the atmosphere when grown in association with cereals (Jensen 1996; Peoples et al 2009), including in rice bean intercropped with maize (Rerkasem, Rerkasem, Peoples et al 1988). The intercrops' total N content and residue N were raised to several times the N in maize sown after residue burning because of the added legume biomass with its higher N concentration. Since the roots and nodules generally represent 30–60% of the total N in legume crops (Peoples et al 2009), more N would have been accumulated by the maize/legume intercrops than the amount found in their aboveground parts when the root and nodule N is accounted for. The N fixed from the atmosphere by the legumes more than compensated for the amount of N removed in the harvested grains of the intercrops, which was twice or more the amount removed in the maize sown after residue burning. The losses of N in the maize sown after residue burning, which include the 10–20 kg N per hectare carried down the slope in runoff and sediment (Punyalue et al 2016) as well as the volatilization in residue burning and the N removal in the harvest of maize grain, are far from being compensated for by fertilizer N.

In conclusion, this study has illustrated the many ways in which processes contributing to sustainability of highland maize production can be stimulated by intercropping maize with legumes. The maize/legume intercrops increased accumulation of N by biological fixation, with 2 important consequences. Soil biodiversity was enhanced, with the diversity and richness of soil animals associated positively with the residue biomass and N content. And the increase in N supply led to the buildup of crop residue that protected the soil surface, suppressed weeds, and enabled the maize to be sown without using fire to clear the land.

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