JARQ 51 (4), 309-318 (2017) https://www.jircas.go.jp

Yield Performance of Upland Rice, Maize and Job's Tears in a Rainfed Upland Ecosystem in Mountainous Laos

Hidetoshi ASAI[1]* and Pheunphit SOISOUVANH[2]

[1] Crop, Livestock and Environment Division, Japan International Research Center for Agricultural Sciences (Tsukuba, Ibaraki 305-8686, Japan)
[2] Biodiversity Unit, Agriculture Research Center, National Agriculture and Forestry Research Institute (Vientiane Capital, Lao P. D. R.)

Abstract

Adaptability to a wide range of environmental factors is a key for achieving stable production in the slash-and-burn (S&B) agriculture of mountainous Laos, where soil varies widely in productivity. Adaptability assessment based on the genotype by environment (GxE) interaction of grain yields in this study entailed an investigation of the yield performance of maize, Job's tears, and seven varieties of upland rice including improved variety B6144F-MR-6-0-0 (B6144), at eleven locations under rainfed upland conditions. Across the eleven locations, the mean yields of upland rice ranged widely from 56 to 583 g m^{-2}. While the GxE interaction was significant, one improved indica variety (B6144) produced high grain yields at all eleven locations. Under low-yielding conditions (56 to 205 g m^{-2} of upland rice), four indica varieties consistently performed with more stable yield performance than three tropical japonica varieties, the poor adaptation of which was attributed to reduced grain number per panicle and the grain-filling ratio. Under moderate- and high-yielding conditions (284 to 583 g m^{-2}), two semi-dwarf varieties - Tampi (tropical japonica) and B6144 (indica) - exhibited the highest productivity due to a higher harvest index (0.40-0.41) compared with the others (0.28 - 0.34), but B6144 likely exhibited lodging signs under fertile soil conditions, where the mean yields were above 360 g m^{-2}. The GxE interaction effect was highly significant among the three upland crops; relative to upland rice, maize was particularly better adapted to moderate-and high-yielding conditions, whereas Job's tears adapted better to low-yielding conditions. Job's tears exhibited stable yield performance across all eleven locations. In contrast, maize had higher yield compared with all upland rice varieties under the adapted conditions, although the upland rice varieties had higher yields compared with maize under unadapted conditions. In conclusion, Job's tears or indica varieties are recommended for growth under low-yielding conditions, and maize or semi-dwarf cultivars are recommended under high-yielding conditions. And with possibly more lodging resistance, the improved indica variety B6144 could be the ideal variety adaptable to a wide range of soil fertility.

Discipline: Crop production
Additional key words: Upland crops, Slash-and-burn agriculture, Genotype by Environment interaction

Introduction

Slash-and-burn (S&B) agriculture has been widely practiced in the mountainous areas of many developing countries (Van Vliet et al. 2012). This is especially true in Lao P.D.R. (hereinafter Laos), which is the most mountainous country in Southeast Asia, with 67% of its surface area having slopes steeper than 30% in the northern part (Inoue et al. 2005). Recent estimates indicated that 17% of the Laotian people still live in S&B agricultural areas, which cover 29% of the country (Messerli et al. 2009). Although the overall time trend variations in the extent of S&B agriculture have exhibited a gradual decrease at the national level, it still persists or has increased in certain rural areas, where the local poverty rate is considerably higher than the national

This paper reports the results obtained in the project on "Establishment of sustainable and independent farm household economy in the rural areas of Indochina (2011 to 2015)" that was jointly conducted with the National Agriculture and Forestry Research Institute in Laos, and sponsored by the Japan International Research Center for Agricultural Sciences.
*Corresponding author: e-mail asai0817@affrc.go.jp
Received 14 February 2017; accepted 30 March 2017.

average of rural areas and the alternatives to S&B agriculture are few (Heinimann et al. 2013).

In these regions, rice (*Oryza sativa*) as a staple food has been traditionally grown in S&B systems by resource-poor subsistence farmers (Linquist et al. 2007). Traditional upland rice cropping still accounts for half of the total rice area in the north, yielding 1.7 t ha^{-1} on average (Ministry of Agriculture Forestry 2004). However, in line with a rapid widespread expansion of the market economy into rural areas, S&B agriculture is shifting from subsistence to market-oriented production. Thus, cultivated crops have been diversified; in particular, the cultivation of maize (*Zea mays*) and Job's tears (*Coix lacryma-jobi* var. *ma-yuen*) has been rapidly expanding to generate cash income (Douangsavanh & Bouahom 2006).

In S&B agriculture, crops are typically grown on the slopes of unbundled fields without fertilization under rainfed upland conditions. On-farm studies have indicated that yield performance varies widely from nothing to 4 t ha^{-1} in the case of upland rice (Roder et al. 1995, Saito et al. 2006b, Asai et al. 2009b). Unstable production has been attributed to environmental heterogeneity, as well as insufficient and irregular rainfall (Roder 2001, Linquist et al. 2006, Saito et al. 2006b). Furthermore, rapid population growth combined with government policies for forest conservation no longer support traditional S&B agriculture with long fallow periods, which has consequently resulted in fallow shortening from 40 years in the 1970s to 5 years by 1992 (Roder et al. 2001), and then to 2 to 3 years in the 2000s in some areas (Linquist et al. 2007). Under short fallow conditions, soil degradation proceeds and thus crop productivity can rapidly decline.

To overcome such destabilization in traditional agricultural systems, soil improvement is a promising approach that can be achieved through nutrient inputs, such as inorganic or organic fertilizer, or with low-input technologies, such as legume fallowing or alley cropping (Roder 2001, Saito et al. 2006a, Saito et al 2008, Asai et al. 2009a). However, fertilizer is expensive and such technologies have been shown to have limited impact on productivity (Roder 2001, Saito et al. 2008, Asai et al. 2009a). Alternative options may include the optimal introduction of upland crops or upland rice varieties to suitable lands where they can adapt better or the identification of ideal types adaptable to a wide range of soil fertility. An ideal type is one that produces high yields not only under infertile soil conditions but also under fertile soil conditions (Ladha et al. 1998).

Traditional rice varieties grown in Laos belong to the tropical japonica group (Sato 1991). These varieties are generally tall, with few tillers and a low harvest index, and suited to fertile soil (Roder et al. 1996, 1997 Saito et al.2006a, Asai et al. 2009b); moreover, these varieties achieve a yield performance of 3-4 t ha^{-1} under favorable conditions (Roder et al. 1996, Saito et al. 2006a, Asai et al. 2009b), but perform very poorly when grown in fields with infertile soil, as many farmers are currently experiencing (Sengxua et al. 2007, Saito et al. 2006a, Asai et al. 2009b). In screening trials in the Lao-IRRI project, several traditional indica varieties were identified as promising varieties with better yield than traditional tropical japonica checks under intensive continuous rice cropping systems (Linquist et al. 2006). Several improved indica varieties with a high harvest index, often referred to as "aerobic rice," were originally developed for rainfed lowland ecosystems or for favorable uplands with sufficient water supply (Atlin & Lafitte 2002, Atlin et al. 2006); these varieties were also found to exhibit high yield performance under unfertilized rainfed upland conditions (Saito et al. 2006a). Several semi-dwarf japonica varieties with harvest indexes as high as those of aerobic rice varieties were also identified in a genotypic resource survey (Asai et al. 2016). However, very few studies have compared the grain yield performance of these diverse varieties under rainfed upland conditions in S&B agriculture. The genotype by environment (GxE) interaction for grain yields is generally larger than the genotype effect under low-yielding conditions (Cooper et al. 1999, Wade et al. 1999), and thus quantitative data are necessary to rigorously compare diverse varieties for identifying the optimal varieties and traits to produce high yields. And despite the growing demand for maize and Job's tears production, there is a lack of available data on the yield performance of these cash crops relative to upland rice.

The objectives of this study were as follows: (1) to compare the grain yield performance of maize, Job's tears, and seven upland rice varieties at multiple locations under rainfed upland conditions in a mountainous area of Laos; and (2) to interpret the impact of GxE interactions on grain yields to assess the adaptability of each crop and variety of upland rice.

Materials and methods

These experiments were conducted at eight locations in 2014 and three locations in 2015 in the Feuang district of Vientiane, Laos. Most of the upland soils in this area are classified as acrisols and are generally reddish brown and moderately acidic, with low water-holding capacity (Matsuo et al. 2015). The mean annual rainfall is approximately 1900 mm, and about 80% of the rainfall occurs during the rainy season between May and October (Fig. 1). The weather data were recorded in a residential area of Nameuang village. All experiments were conducted on farmers' fields located within a 9-km distance from the weather station. Therefore, the climate conditions were similar at the locations in each year.

The experiment locations were typical of upland rice farming in a mountainous area of Laos. Table 1 presents general information about the locations and their codes. The topographical characteristics ranged from 8% to 50% in slope gradient, and from 299 m to 499 m in elevation. The cropping history varied from more than 20 years of fallow to three years of continuous annual upland rice cropping.

In the experiment, three upland crops, including local Job's tears, hybrid maize and seven varieties of upland rice, were grown together at eleven locations under rainfed upland conditions. Seven varieties of upland rice included six traditional varieties and one improved variety. The traditional varieties were comprised of three indica varieties (Parezue, Non and Laboun) and three tropical japonica varieties (Tampi, Nok and Makhingsung (Mak)). Two of the six traditional varieties, Tampi and Parezue, were the most popular local varieties in the study area. Tampi has been described as a cultivar with semi-dwarf traits and strong culm for lodging resistance. The other traditional varieties include those that were selected through a screening trial in the Lao-IRRI project (Linquist et al. 2006). One improved variety, B6144F-MR-6-0-0 (B6144), has been referred to as "aerobic rice" due to its adaptability to non-saturated soil moisture conditions and is an elite variety developed in Indochina. The maize tested here is a single crossing hybrid (LVN10) developed in Vietnam.

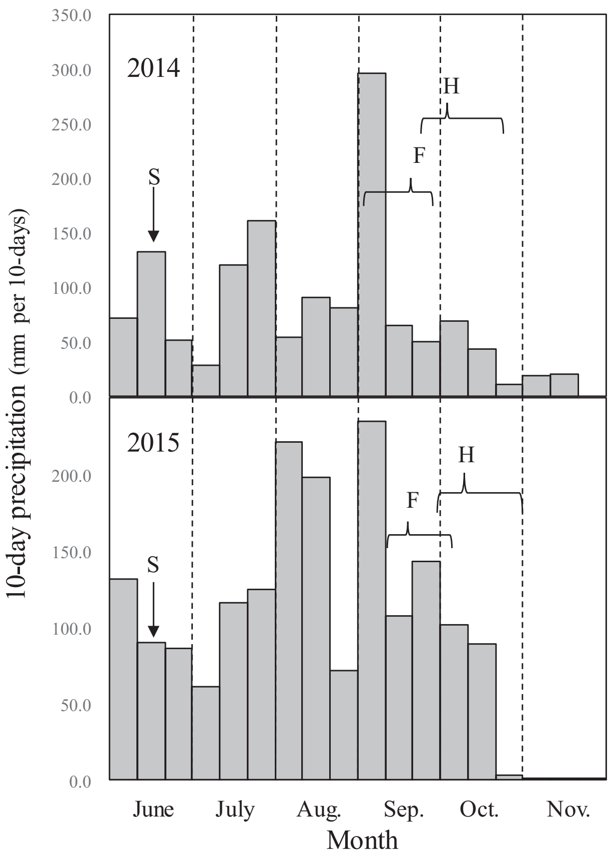

Fig. 1. Rainfall accumulation over a 10-day period (for each bar) during the 2014 and 2015 rice cropping seasons (from Jun. to Nov.) in Nameuang village in Feuang District, Vientiane Province.

'S', 'F' and 'H' denote the time of sowing, flowering and harvesting, respectively.

At each location, four replicates were prepared with a randomized complete block design. The individual plot sizes were 2.5 m × 2.5 m for upland rice, 2.5 m × 5.0 m for Job's tears, and 2.5 × 7.5 m for maize, respectively. The seeds were planted with a dibble stick, as is done in traditional practice, with a hill spacing of 0.25 m × 0.25 m and 10-15 seeds for upland rice, 0.25 m × 0.50 m with 3-5 seeds for Job's tears, and 0.25 m × 0.75 m with 5-7 seeds for maize; therefore, the planting density in a plot was 10 x 10 hills for each crop. Fertilization and tillage were not conducted at any location. Planting was conducted in both years from the 13th to 16th of June 2014 and 2015. Weeding was manually controlled during a one-month interval. For lodging prevention, plants in the plots with a lodging sign were fixed by setting rope in a matrix with two hill intervals. At maturity in all plots, the grain yields were measured by harvesting from whole plots, except for the two border rows on each side of the plot. In the case of upland rice plots, six rice hills were systematically sampled from each plot to determine the plant height and yield components. After threshing, the filled grains were separated from unfilled ones by submerging them in tap water. One-thousand filled and unfilled grains were taken as a representative sample to count the number of grains. The dry weights of 1000 filled and unfilled grains were measured after oven drying at 65°C for at least 48 h. The dry weight of the filled grains was referred to as the grain weight in this study. Then, the grain number per panicle (total grain number of six hills/panicle number of six hills) and the grain-filling ratio (filled grain number/total grain number) were calculated.

For soil chemical analysis, the top soil samples from a depth of 0-10 cm were collected at planting with a soil auger of 1.5 cm in diameter. Twelve cores from each location were pooled, air-dried and 2 mm-sieved for soil analysis. The soil pH was determined in a 1:2.5 ratio of soil:water; the extractable P was determined using the Bray 2 method (Bray and Kurtz 1945); total C and N were determined using a combustion method with a CN elemental analyzer (JM3000N, J-Science Lab Co., Ltd., Kyoto, Japan); and the exchangeable aluminum was determined by using the KCl extraction method and exchangeable bases with an ammonium acetate extract method at pH 5.0 and 7.0 (Soil and Plant Analysis Council, 1999).

An analysis of variance (ANOVA) was conducted for the combined data set across the eleven locations (eight locations in 2014 and three locations in 2015). An analysis was conducted separately among the three upland crops and among seven upland rice varieties. In this analysis, we considered the effects of genotype (G), environment (E) and their interaction (G×E) as fixed variables, while the replicates nested within the environment were considered random. In an analysis of three uplands crops, the grain yield of upland rice was averaged over seven genotypes. For the interpretation of the GxE interaction effect for grain yields, a Finlay-Wilkinson regression analysis was used for three upland crop comparisons, and a GGE (genotype main effect plus GxE interaction) biplot model was used for a comparison of seven upland rice varieties.

Results

The soils at the eleven locations were generally moderately acidic, ranging in pH from 4.3 to 6.0 (Table 1). The soil properties ranged from 16.2 to 34.1 g kg^{-1} total C, with an average C/N ratio of 11.3 and available P from 2.9 to 39.7 mg-P kg^{-1}. The parameters of exchangeable Al and exchangeable Ca varied largely among locations, ranging from 0 to 1.3 cmol kg^{-1} and from 0.4 to 8.0 cmol kg^{-1}, respectively. The pH parameter was positively correlated with total C (r=0.87, $P < 0.01$), total N (r=0.87, $P < 0.01$), and exchangeable Mg (r=0.91, $P < 0.01$) and was negatively correlated with exchangeable Al (r=0.89, $P < 0.01$). The other parameters of elevation, slope and cropping history exhibited no correlation with any of the soil chemical properties.

The mean grain yields varied among locations, ranging from 56 to 583 g m^{-2} in upland rice, from 12 to 1079 g m^{-2} in maize and from 124 to 491 g m^{-2} in Job's

Table 1. Description, soil properties and grain yields of three upland crops in eleven environments in Nameuang village

	S1*	S2*	S3	S4	S5	S6	S7	S8	S9*	S10	S11
Elevation (m)	449	447	392	322	305	314	453	499	432	472	299
Slope gradient (%)	8%	13%	50%	32%	24%	19%	28%	29%	11%	10%	21%
Cropping history	More than 20yrs fallow	Upland rice in wet season 2013	More than 20yrs fallow	Upland rice in wet season 2013	Upland rice in wet season 2011-2013	3yrs fallow	4 yrs fallow	Upland rice in wet season 2013	More than 20yrs fallow	More than 20yrs fallow	2yrs fallow
Year of cropping	2014								2015		
Sowing date	15-Jun	16-Jun	14-Jun	14-Jun	13-Jun	13-Jun	15-Jun	16-Jun	14-Jun	14-Jun	13-Jun
Days to flowering	101	106	94	95	99	97	95	95	110	98	101
pH (H_2O)	5.7	5.8	4.5	5.3	4.3	4.6	5.3	5.6	5.6	6.0	4.7
Total C (g kg^{-1})	30.3	29.1	16.9	16.2	18.3	18.5	24.4	25.8	30.5	34.1	17.2
Total N (g kg^{-1})	2.5	2.7	1.5	1.5	1.6	1.6	2.3	2.4	2.7	2.9	1.5
C/N	12.3	10.8	11.1	10.8	11.2	11.3	10.5	10.9	11.3	12.0	11.5
Avail P (mgP kg^{-1})	6.8	2.9	18.6	39.7	25.9	23.6	5.9	19.0	17.7	11.1	23.3
Exc. Al^{3+} (cmol kg^{-1})	0	0	0.5	0.0	1.3	1.0	0.0	0.0	0.0	0.0	0.7
Exc. Ca (cmol kg^{-1})	2.4	1.4	0.4	3.9	1.0	1.0	7.2	8.0	4.5	2.1	0.9
Exc. K (cmol kg^{-1})	1.0	0.4	0.6	0.9	0.5	0.9	0.3	1.1	0.5	1.0	0.8
Exc. Mg (cmol kg^{-1})	2.5	2.4	0.3	0.8	0.4	0.6	2.3	2.0	1.7	2.5	0.5
Mean grain yield (g m^{-2})											
Upland rice	114	56	205	301	95	161	360	583	62	284	170
Maize	13	12	57	154	48	56	684	1079	13	319	57
Jobs' tears	141	124	204	491	186	185	325	387	131	278	203

* The soils of S1, S2 and S9 were categorized as black soil.

tears (Table 1). The yields of upland rice and maize were highest in S8, whereas the yield of Job's tears was highest in S4. Three locations with black soil (S1, S2 and S9) exhibited the lowest grain yields for all the upland crops, regardless of a high total C content or moderate soil fertility. Except for three black-soil locations, higher grain yields of upland rice and maize were closely associated with higher exchangeable Ca (r =0.93 and 0.90, P < 0.01, Fig. 2). The grain yields of Job's tears were also significantly correlated with exchangeable Ca (r =0.71, P < 0.05), but the relationship was not clear compared with those of the other two crops.

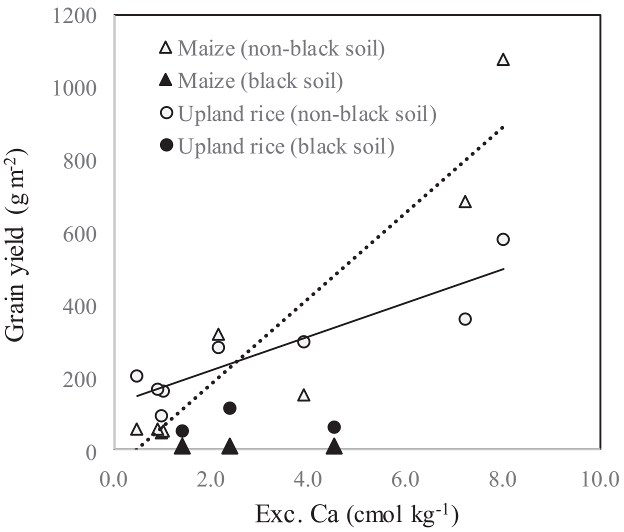

Fig. 2. The relationship between grain yields in upland rice and maize with exchangeable Ca (Exc. Ca) content in the 0-10 cm soil layer.

ANOVA results for seven upland rice varieties indicated that the effect of G, E and the G×E interaction were highly significant for all parameters of plant height, days to flowering, grain yield and yield components (Table 2). The yield performance averaged over the eleven locations showed that the improved variety (B6144) and the other three traditional varieties (Parezue, Non and Tampi) produced higher yields (231 to 243 g m^{-2}) than the others. The indica varieties including B6144 generally produced higher panicle numbers (174 to 208 vs. 127 to 135 panicles m^{-2}) with lower grain weight (20.6 to 24.2 vs. 30.6 to 32.4 mg $grain^{-1}$) than the japonica varieties. The days to flowering varied from 88 days for Laboun to 116 days for Tampi, and the two early-maturing varieties (Laboun and Nok) tended to exhibit lower yields. Two varieties (B6144 and Tampi) exhibited smaller plant height than the other varieties but produced the highest yields in each group of Indica and Japonica, respectively. Tampi, a local japonica variety, never exhibited lodging signs at any location. Two varieties (Non and Laboun) exhibited lodging signs at four sites (S4, S7, S8, S10),

Table 2. Grain yield, yield components, plant height and days to flowering of seven upland rice varieties in eleven environments

	Plant height (cm)	Days to Flowering (days)	Yield (g m^{-2})	Harvest index	Total biomass (g m^{-2})	Panicle num. (panicle m^{-2})	Grain num. per panicle (grain $panicle^{-1}$)	Grain-filling ratio	1000 grain weight (mg $grain^{-1}$)
Tampi	82 c	116 a	235 ab	0.33 ab	660 b	137 c	69 b	0.69 b	30.6 c
Makhingsung	99 b	102 b	199 bc	0.28 c	654 b	125 c	85 a	0.52 c	31.1 b
Nok	96 b	98 c	197 bc	0.29 bc	587 b	127 c	67 bc	0.56 c	32.4 a
Parezue	99 b	103 b	243 ab	0.33 ab	737 b	167 b	69 b	0.73 ab	22.9 e
B6144	82 c	98 c	254 a	0.39 a	642 b	208 a	68 b	0.68 b	20.6 f
Non	108 a	103 b	231 ab	0.28 c	871 a	196 a	55 d	0.76 a	23.0 e
Laboun	98 b	88 d	184 c	0.29 c	661 b	174 b	55 cd	0.69 b	24.2 d
F ratios from ANOVA analysis									
Site	54.3 ***	30.0 ***	91.2 ***	21.4 ***	82.5 ***	39.7 ***	32.8 ***	15.5 ***	118.0 ***
Var	36.6 ***	151.2 ***	5.5 ***	13.4 ***	8.0 ***	38.3 ***	12.1 ***	50.1 ***	1044.8 ***
Site x Var	4.2 ***	6.3 ***	1.8 **	3.2 ***	3.2 ***	1.7 **	2.4 ***	4.0 ***	4.6 ***

Means sharing the same superscript are not significantly different from each other (Tukey's HSD, $P < 0.05$).
** Significant at the 0.01 level.
*** Significant at the 0.001 level.

whereas other varieties including B6144 did so at two locations (S7, S8).

For interpretation of the GxE interactions in upland rice varieties, Fig. 3 presents a polygon-view of the GGE biplot. The first and second principal component axis accounted for 49.8% and 34.1% of the total variance, respectively. The visualization clarified that the eleven environments were classified into three groups, with the seven varieties classified into three groups. Environmental grouping was strongly related to environment mean grain yield. One location with the highest grain yield level (S8, 583 g m^{-2}) and three locations with moderate grain yield level (S4, S7 and S11, 284 to 360 g m^{-2}) of the eleven locations were categorized into environment groups EG1 and EG2, respectively. The remaining seven locations (56 to 205 g m^{-2}) with low grain yield level, including three locations with black soil, were categorized into EG3.

For genotypic classification, japonica varieties and indica varieties were classified as GG1 and GG2, respectively (Fig. 3), with the exception of one indica variety (Laboun) classified as GG3. The mean grain yields of GG1 and GG2 were 628 g m^{-2} and 620 g m^{-2} in EG1 and 333 g m^{-2} and 337 g m^{-2} in EG2, respectively, whereas GG2 out-yielded GG1 in EG3 (151 vs. 98 g m^{-2}) (Table 3). GG3 also exhibited higher grain yields in EG3 than GG1 (130 vs. 98 g m^{-2}) as well as GG2, but its yield performance was worse than GG1 and GG2 in the moderate- and high-yielding environments of EG1 and EG2. The percentage yield in EG3 compared to the average yields of the other two EGs were 24.1 to 24.3% for GG1, 35.2 to 37.9% for GG2 and 46.9% for GG3, respectively, indicating a tendency for the japonica variety (GG1) to adapt better to moderate- and high-yielding environments, while the indica varieties (GG2 and GG3) demonstrated stable yield performance across the wide range of environments.

The large difference in grain yield of GG1 between EG3 and the other EGs was attributed to grain number per panicle and the grain-filling ratio of GG1 (Table 4). The grain number per panicle of GG1 in EG3 was 41.6 - 44.2% of the average in EG1 and EG2, whereas the grain number per panicle of GG2 in EG3 was 51.4 - 57.0% of the average in EG1 and EG2. The grain-filling ratio of GG1 in EG3 was 75.0 - 83.8% of the average of EG1 and EG2, and was lower than in GG2 (91.3 - 97.0%). Similar differences were also observed in the harvest index (72.7 - 79.4% in GG1 vs. 96.4 - 101.3% in GG2) and plant biomass (29.1 - 30.8% in GG1 vs. 36.6 - 39.3% in GG2).

Two varieties - Tampi (GG1) and B6144 (GG2) - exhibited the highest yield performance both in EG1 (677 and 627 g m^{-2}) and EG2 (378 and 352 g m^{-2}) (Table 3). Both varieties exhibited shorter plant heights with a higher harvest index (Table 2). Under these conditions, the genotypic difference of grain yield correlated significantly with only the harvest index ($r = 0.79$, $n = 7$).

The results of the combined ANOVA analysis for the grain yield of three crops across the eleven locations indicated that the G × E interaction effect was highly

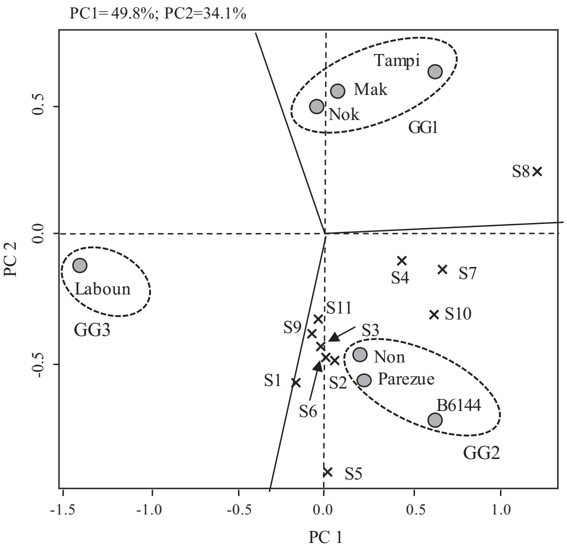

Fig. 3. Scatter plot diagram of the GGE-biplot of seven upland rice varieties and eleven environments.

Table 3. Grain yield of maize, Job's tears and seven upland rice varieties in three environmental groups (EG)

		EG1	EG2	EG3	Yield ratio
			g m^{-2}		EG3/(EG1+2)
Maize		1079	386	37	6.6%
Job's tear		377	354	168	46.7%
Upland rice			321	124	32.0%
Tampi	GG1	677	378	110	24.3%
Mak	GG1	599	315	93	24.1%
Nok	GG1	607	305	92	24.2%
Parezue	GG2	627	327	152	37.9%
B6144	GG2	653	352	155	36.4%
Non	GG2	580	331	139	35.2%
Laboun	GG3	402	237	130	46.9%
Average	GG1	628	333	98	24.2%
Average	GG2	620	337	149	36.5%
Average	GG3	402	237	130	46.9%

Table 4. Yield components of seven upland rice varieties in three environmental groups (EG)

	Harvest index				Total biomass				Panicle number			
	EG1	EG2	EG3	Ratio	EG1	EG2	EG3	Ratio	EG1	EG2	EG3	Ratio
				EG3/(EG1+2)	g m^{-2}			EG3/(EG1+2)	panicle m^{-2}			EG3/(EG1+2)
Tampi	0.40	0.41	0.29	72.7%	1813	990	355	29.1%	179	165	120	71.4%
Mak	0.32		0.25	75.8%	1823	968	353	29.9%	191	152	108	66.7%
Nok	0.33	0.34	0.27	79.4%	1707	829	323	30.8%	194	150	112	69.6%
Parezue	0.33	0.33	0.34	101.3%	1941	1021	443	37.1%	247	216	159	71.1%
B6144	0.40	0.40	0.39	96.4%	1683	848	405	39.3%	329	254	182	67.0%
Non	0.28	0.29	0.28	98.4%	2085	1251	535	36.6%	237	238	173	72.9%
Laboun	0.28	0.29	0.29	99.8%	1422	844	474	48.0%	201	178	168	91.0%

	Grain number per panicle				Grain-filling ratio				Grain weight			
	EG1	EG2	EG3	Ratio	EG1	EG2	EG3	Ratio	EG1	EG2	EG3	Ratio
	grain $panicle^{-1}$			EG3/(EG1+2)				EG3/(EG1+2)	mg $grain^{-1}$			EG3/(EG1+2)
Tampi	141	96	46	43.1%	0.84	0.79	0.60	75.0%	30.2	32.4	29.8	93.5%
Mak	167	123	56	41.6%	0.69	0.58	0.48	79.9%	31.2	32.0	30.6	96.2%
Nok	133	94	46	44.2%	0.70	0.60	0.52	83.8%	32.8	33.9	31.7	94.4%
Parezue	132	84	53	53.8%	0.83	0.77	0.71	91.3%	23.7	24.5	22.1	91.1%
B6144	118	92	51	51.4%	0.75	0.72	0.70	97.0%	22.6	22.1	20.7	92.8%
Non	105	65	43	57.0%	0.85	0.78	0.73	91.5%	24.1	25.0	21.9	88.6%
Laboun	93	70	44	57.7%	0.73	0.70	0.70	98.3%	24.8	25.2	23.7	94.4%

significant (data not shown), but the G effect was not significant and the mean grain yields averaged over the eleven locations were 2.27 t ha^{-1} for maize, 2.38 t ha^{-1} for Job's tears and 2.19 t ha^{-1} for upland rice with no significant differences. The stability parameter obtained from Finlay and Wilkinson's regression analysis was 0.48 for Job's tears and 1.70 for maize; upland rice exhibited intermediate stability (0.79) (Fig. 4). Relative to upland rice, maize was well adapted to high- and moderate-yielding conditions, whereas Job's tears adapted well to low-yielding conditions. Job's tears exhibited the most stable yield performance across the eleven locations (Table 3). Conversely, maize produced higher grain yields than any of the upland rice varieties or Job's tears both in moderate-and high-yielding conditions, whereas its yield performance was the poorest in low-yielding conditions.

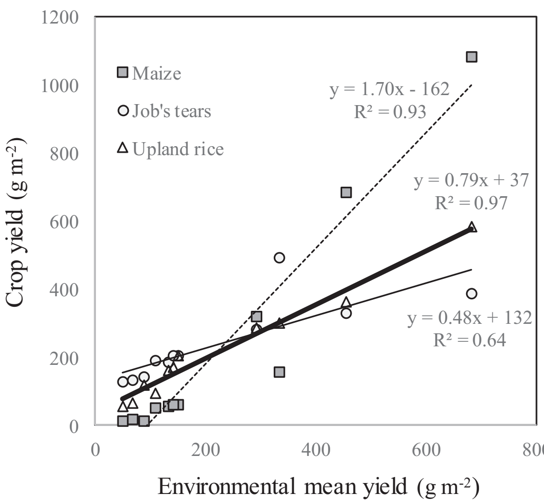

Fig. 4. The relationship between three upland crops and the environmental mean yields.
Grain yields of upland rice were averaged over the seven varieties.

Discussion

This study rigorously investigated the yield performance of maize, Job's tears and seven upland rice varieties under multiple rainfed upland conditions in S&B agriculture. While the GxE interaction effect for grain yields was highly significant in a trial of upland rice comparisons, one improved indica variety (B6144) consistently exhibited high productivity in the three environmental groups, including under low and high yielding conditions. This is consistent with previous studies in the Philippines (Atlin et al. 2006), northern Laos (Saito et al. 2006a, Asai et al. 2009b) and West

Africa (Saito & Futakuchi 2009). Two traditional indica varieties (Non and Parezue) and one traditional japonica variety (Tampi) also exhibited higher productivity than the other traditional varieties. However, the environmental adaptability differed among the three varieties; Non and Parezue adapted better to low-yielding conditions, whereas Tampi was particularly well adapted to moderate- and high-yielding conditions due to the long growth duration and strong resistance to lodging.

Under low-yielding conditions, indica varieties, including both improved and traditional varieties, consistently demonstrated more stable yield performance than japonica varieties. The poor adaptation of japonica varieties to low-yielding conditions was the result of reduced grain numbers per panicle and a decreased grain-filling ratio, but these parameters were well maintained by indica varieties, as was previously reported by Asai et al. (2009b). The superiority of indica varieties was also consistently confirmed under unfavorable upland conditions in past field trials conducted in Luang Prabang Province, where yield levels were within a range of 0.5 to 1.8 t ha^{-1} (Linquist et al. 2007, Sengxua et al. 2007, Asai et al. 2009b). As was observed in this study, indica varieties in the tropics had in common vigorous tillering traits with small-sized grains (Takahashi 1984). Most farmers believed that the small-grain variety can adapt well to poor soils (Saito et al. 2006c). In a germplasm survey where 244 accessions were collected from northern, central and southern Laos, Asai et al. (2016) also found from their collected dataset that good tillering ability and small grain size were significantly effective indicators of genotypic adaptability to infertile soil conditions.

In contrast, adaptation to moderate- to high-yielding conditions, observed for B6144 and Tampi, was attributed to a semi-dwarf characteristic. Traditional varieties are generally tall and thus have a low harvest index (Roder et al. 1996, Saito et al. 2006a). An exceptional variety was Tampi, which exhibited semi-dwarf traits with high culm strength. Under moderate- and high-yielding conditions, where the environmental mean yields of upland rice were above 2.8 t ha^{-1} in our study, two varieties (B6144 and Tampi) exhibited higher HI (0.40 to 0.41) than the other varieties (0.28 to 0.34) because of a semi-dwarf characteristic, whereas total biomass production was intermediate and was lower than that of Non and Parezue. This result is consistent with the previous study comparing semi-dwarf and traditional cultivars of lowland rice, which attributed improvement in yield potential to increased HI rather than to biomass production (Evans et al. 1984). Similarly, it has also been reported that a high HI has an advantage in nutrient use efficiency of N and P (Inthapanya et al. 2000), and the improved indica varieties that exhibited high HI are likely to perform well under a wide range of environments, including low-yielding conditions (Atlin et al. 2006, Saito et al. 2006a). However, in the case of Tampi, HI was drastically reduced to a level similar to that of other japonica varieties under low-yielding conditions. In addition to improved HI, the semi-dwarf cultivars have another benefit that makes the plants more resistant to lodging. As was observed in this study, traditional varieties with high plant height, which are susceptible to flattening by rain and wind, likely lodge, especially under fertile soil conditions. This often results in large yield losses but also increases the labor requirement for harvest operation. In particular, the local semi-dwarf variety (Tampi) was more resistant to lodging than B6144 due to its strong culm. Thus, the introduction of a semi-dwarf cultivar with high culm strength is desirable when farmers grow upland rice in fertile soil conditions.

Relative to upland rice, maize is particularly well adapted to moderate- and high-yielding conditions, while Job's tears adapted better to low-yielding conditions. Maize had a higher yield compared with any of the upland rice varieties under the adapted environments; however, the upland rice varieties had higher yields than maize in the unadapted environments, but exhibited very low yield performance ranging from 0.1 to 0.6 t ha^{-1} under infertile soil conditions (versus 0.6 to 2.1 t ha^{-1} in upland rice). Maize was generally superior to upland rice in terms of water-capturing capacity (Kondo et al. 2002). There was sufficient precipitation during the growth periods. Thus, the inferiority of maize could be attributed to a soil nutrient deficiency rather than drought stress. In Sanyabury Province of Laos, the introduction of tillage systems on steep slopes achieved 4 to 5 t ha^{-1} of maize yield on average without fertilizer input, but also caused serious soil erosion problems that accelerated environmental vulnerability (Lestrerin et al. 2012). Alternative options could be the production of Job's tears in place of maize. The good adaptability to infertile soil conditions and stable yield performance was also recognized by upland farmers with local indigenous knowledge (Saito et al 2006c). Furthermore, upland farmers also regard Job's tear as a crop that requires minimal care for weeding (Douangsavanh & Bouahom 2006). Since weed infestation is one of the significant constraints on S&B agriculture, and often occurs in fields with low yields after short fallows (Roder et al. 1997), the introduction of Job's tears is highly profitable in infertile soil conditions that many farmers are currently experiencing.

Our results suggest that specific adaptations are likely to provide a significant yield advantage in particular environments without fertilization; Job's tears or an indica variety is preferable in infertile soil conditions, whereas a semi-dwarf cultivar or maize is preferable in fertile soil conditions. The improved indica variety with semi-dwarf traits and high HI (B6144) not only improves productivity under fertile soil conditions but also adapts well to infertile soil conditions. However, this improved indica variety is non-glutinous with small grain size, and such grain quality was minimally accepted by Lao consumers, who prefer to eat glutinous rice with large grain size (Songyikhangsuthor et al. 2002). For wider acceptance, an improved variety with desirable grain qualities must be developed. Furthermore, the mechanism of adaptation involving crops and rice varieties remains unclear, and thus requires further research. Finally, it should be noted that the optimum selection of crops or varieties should only be seen as one strategy for improving upland rice-based cropping systems, as higher crop productivity can lead to greater nutrient withdrawal and soil degradation (Saito et al. 2006b, Asai et al. 2007). Therefore, integrated soil fertility management practices and land use management need to be developed for the effective use of upland crops and upland rice varieties with different levels of adaptability to soil conditions.

Acknowledgements

This study was conducted as part of a project sponsored by the Japan International Research Center for Agricultural Sciences on "Establishment of sustainable and independent farm household economy in rural areas of Indochina." The authors would like to thank Mr. Banthasack Vongphouthone for the preparation of seeds and Mr. Vilaxay Kabae for his assistance in the field work and collection of data.

References

Asai, H. et al. (2007) Quantification of soil organic carbon dynamics and assessment of upland rice productivity under the shifting cultivation systems in northern Laos. *In* Proceedings of the 2nd International Conference on Rice for the Future, Bangkok, Thailand, 9-13.

Asai, H. et al. (2009a) Biochar amendment techniques for upland rice production in northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. *Field Crops Res.*, **111**, 81-84.

Asai, H. et al. (2009b) Yield response of *indica* and tropical *japonica* genotypes to soil fertility conditions under rainfed uplands in northern Laos. *Field Crops Res*, **112**, 141-148.

Asai, H. et al. (2016) Identification of key agronomic traits for farmer's variety selection in rainfed upland rice systems of Laos. *Jpn J. Trop. Agr.*, **9**, 52-58. [In Japanese with English summary].

Atlin, G. N. & Lafitte, H. R. (2002) Developing and testing rice varieties for water-saving systems in the tropics. *In* Water-wise rice production. Proc. of the Int. Workshop on Water Wise Rice Production, eds. B. A. M. Bouman et al., International Rice Research Institute., Los Baños, Philippines. 275-283.

Atlin, G. N. et al. (2006) Developing rice cultivars for high-fertility upland systems in the Asian tropics. *Field Crops Res.*, **97**, 43-52.

Bray, R. H. & Kurtz, L. T. (1945) Determination of total, organic and available forms of phosphorus in soil. *Soil Sci.*, **59**, 39-45.

Cooper, M. et al. (1999) Rainfed lowland rice breeding strategies for Northeast Thailand.: I. Genotypic variation and genotype × environment interactions for grain yield. *Field Crops Res.*, **64**, 131-151.

Douangsavanh, L. & Bouahom, B. (2006) Pathways out of Poverty through Maize and Job's Tear in Lao People's Democratic Republic. CAPSA Working Paper No. 92. United Nations, ESCAP, Bangkok, pp. 100.

Evans, L. T. et al. (1984) Morphological and physiological changes among rice varieties used in the Philippines over the last seventy years. *Field Crops Res.*, **8**, 105-124.

Heinimann, A. et al. (2013) Socio-Economic Perspectives on Shifting Cultivation Landscapes in Northern Laos. *Hum. Ecol.*, **41**, 51-62.

Inoue Y. et al. (2005) Assessing the change of land-use and carbon sink capacity in the shifting cultivation region of northern Laos. *In* Proceedings of the International Geoscience and Remote Sensing Symposium (IGARSS) 2005, Seoul, Korea, 3098-3100.

Inthapanya P. et al. (2000) Genotype differences in nutrient uptake and utilisation for grain yield production of rainfed lowland rice under fertilised and non-fertilised conditions. *Field Crops Res.*, **65**, 57-68.

Kondo, M. et al. (2002) Characteristics of root growth and water uptake from soil in upland rice and maize under water stress. *Soil Sci. Plant Nutr.*, **46**, 721-732.

Ladha, J. K. et al. (1998) Opportunities for increased nitrogen-use efficiency from improved lowland rice germplasm. *Field Crops Res.*, **56**, 41-71.

Lestrerin, G. et al. (2012) Conservation agriculture in Laos: Diffusion and determinants for adoption of direct seeding mulch-based cropping systems in smallholder agriculture. *Renew Agr. Food Syst.*, **27**, 81-92.

Linquist, B. A. et al. (2006) Improving upland rice-based cropping systems in Laos. *In* Rice in Laos, eds. Schiller, J. M., et al., International Rice Research Institute, Los Baños, Philippines, 391-407.

Linquist, B. A. et al. (2007) Montane Paddy Rice: Development and Effects on Food Security and Livelihood Activities of Highland Lao Farmers. *Mountain Res. Dev.*, **27**, 40-47.

Matsuo, K. et al. (2015) Present Soil Chemical Status and Constraints for Rice-Based Cropping Systems in Vientiane Plain and Neighboring Areas, Lao PDR. *Plant Prod. Sci.*, **18**, 314-322.

Messerli, P. et al. (2009) Finding Homogeneity in Heterogeneity—A New Approach to Quantifying Landscape Mosaics Developed for the Lao PDR. *Hum. Ecol.*, **37**, 291-304.

Ministry of Agriculture Forestry (2004) Agricultural Statistics: Yearbook 2004. Vientiane capital, Lao PDR.

Roder, W. et al. (1995) Relationships between soil, fallow period, weeds and rice yield in slash-and-burn systems of Laos. *Plant and Soil*, **176**, 27-36.

Roder, W. et al. (1996) Glutinous Rice and Its Importance for Hill Farmers in Laos. *Econ. Bot*. **50**, 401-408.

Roder, W. et al. (1997) Weeds in slash-and burn rice fields in northern Laos. *Weed Res*., **37**, 111-119.

Roder, W. (2001) Slash-and-Burn Rice Systems in the Hills of Northern Laos PDR: Description, Challenges and Opportunities. International Rice Research Institute, Los Baños, Philippines, pp.201.

Saito, K. et al. (2006a) Response of traditional and improved upland rice cultivars to N and P fertilizer in northern Laos. *Field Crops Res*., **96**, 216-223.

Saito, K. et al. (2006b) Cropping intensity and rainfall effects on upland rice yields in northern Laos. *Plant and Soil*, **284**, 175-185.

Saito, K. et al. (2006c) Farmers' knowledge of soils in relation to cropping practices: A case study of farmers in upland rice based slash-and-burn systems of northern Laos. *Geoderma*, **136**, 64-74.

Saito, K. et al. (2008) Planted legume fallows reduce weeds and increase soil N and P contents but not upland rice yields. *Agroforest. Syst*., **74**, 63-72.

Saito, K. & Futakuchi, K. (2009) Performance of diverse upland rice cultivars in low and high soil fertility conditions in West Africa. *Field Crops Res*., **111**, 243-250.

Sato, Y. (1991) Variation in spikelet shape of the indica and japonica rice cultivars in Asian origin. *Jpn. J. Breed*., **41**, 121-134 [In Japanese with English summary].

Sengxua, P. et al. (2007) The effect of tillage on performance of upland rice varieties in northern Laos. *Khon Kaen Agric. J*., **35**, 70-83.

Soil and Plant Analysis Council (1999) Soil Analysis Hand Book of Reference Methods. CRC Press LLC, Boca Raton, pp.247.

Songyikhangsuthor, K. et al. (2002) Participatory varietal selection: Lessons learned from the Lao upland programme. *In* Breeding rainfed rice for drought-prone environments: Integrating conventional and participatory plant breeding in South and Southeast Asia., eds. J. R. Witcombe et al., Proc. of a DFID Plant Sciences Research Programme/IRRI Conf., Los Baños, Laguna, Philippines, 49-52.

Takahashi, N. (1984) Differentiation of Ecotypes in Oryza Sativa L. *In* Biology of rice, eds. Tsunoda, S. & Takahashi, N., Elsevier, Tokyo Japan, **7**, 31-67.

Van Vliet, N. et al. (2012) Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: A global assessment. *Glob. Environ. Chang*., **22**, 418-429.

Wade, L. J. et al. (1999) Genotype by environment interactions across diverse rainfed lowland rice environments. *Field Crops Res*., **64**, 35-50.