Integrated On-Farm Crop Diagnosis of Upland Rice Yields in Northern Thailand

K. Van Keer[1] and G. Trébuil[2]

Abstract

In northern Thailand, swidden cultivation of upland rice (*Oryza sativa* L.) is still an important component of remote highland farming sytems. Under no-external-input cropping systems, yields in farmers' fields are generally low (1-1.5 t ha^{-1}), but quite variable. Yields of 3 and 4 t ha^{-1} for early- and late-maturing varieties, respectively, are observed in pockets in farmers' fields. But such yields are seldom achieved because of multiple and interacting permanent or transient limiting factors. Identifying and ranking these limiting factors is a prerequisite to setting research and extension priorities for improving current farmers' practices. An on-farm diagnostic survey was therefore carried out in a remote highland village of Fang District, Chiang Mai Province (600-800 masl), to identify, date, and rank the environmental and cropping system variables causing major yield limitations in upland rice under actual farmers' circumstances and management practices.

Data on the crop population status for two early- and late-maturing types of local cultivars, crop environmental conditions, and cropping practices were obtained by monitoring 432 squares in 63 Lahu farmers' fields on deep granitic Acrisol soils with a clay-loamy texture during four cropping seasons. An empirical model of yield buildup and phase realization indices were used to date and rank the periods of yield differentiation and principal component analyses with instrumental variables were carried out to identify the factors affecting yields and their components.

For the reproductive phase, the analysis of rice yield buildup processes pinpointed panicle formation and spikelet differentiation as key periods of yield differentiation. During the vegetative period, poor crop biomass accumulation was more important than low plant density. Vegetative biomass accumulation per plant also influenced panicle and spikelet formation. The analysis of pooled data revealed strong negative relationships for (a) no. of panicles $plant^{-1}$ and no. of spikelets $panicle^{-1}$ vs rice root aphid infestation; (b) plant density vs late weed competition and late-maturing cultivars (sown at lower densities); and (c) percentage of filled spikelets and 1000-grain weight vs 1995 wet season, which was characterized by dry spells during the vegetative and the reproductive phases. Weak negative relationships were found for no. of panicles $plant^{-1}$ vs slope angle, erosion, no. of successive upland rice crops, minimum tillage, and early weed stress. A weak positive correlation between the older secondary forest type of fallow and upland rice grain yield was also observed. Brown spot was the only disease having some limited effect on crop productivity, especially for late-maturing varieties.

Rice root aphid infestation was identified as the single major limiting factor with a strong and consistent effect on final grain yields. Weed competition was found to be the second most important yield-limiting factor, followed by soil erosion in sloping fields after shallow tillage. These results show that attention should be paid to the management of soil-borne pests when setting priorities for improving upland rice-based cropping systems in northern Thailand highlands.

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1 Soil scientist, Laboratory of Soil Fertility and Soil Biology, Katholieke Universiteit Leuven , 3001 Heverlee, Leuven, Belgium.
2 Systems agronomist, IRRI Thailand Office, seconded from Food Crops Program, Cirad-CA, Montpellier, France.

Introduction and research objectives

In peninsular Southeast Asia, swidden cultivation of upland rice (*Oryza sativa* L.) is still an important component of remote highland farming systems (Piggin et al 1998). In northern Thailand, these systems are presently in transition to semi-permanent or permanent types of cropping systems (Trebuil et al 2000). Under no-external-input cropping systems, grain yields in farmers' fields are generally low (1-1.5 t ha^{-1}), but quite variable (Kunstadter 1978, Ramakrishnan 1992). Yields of 3 and 4 t ha^{-1} for early- and late-maturing local varieties, respectively, are observed in pockets in farmers' fields (Van Keer et al 1998). But such relatively high yields are seldom achieved because of multiple and interacting permanent or transient limiting factors that characterize such an unfavorable rice ecosystem. Identifying and ranking these limiting factors is a prerequisite to setting research and extension priorities for improving current farmers' practices and reducing yield gaps (Dore et al 1997).

On the basis of a previous assessment of the key characteristics of local upland rice (UR) planting material, an interpretative empirical model of yield buildup processes of the UR crop was constructed to be used for on-farm crop diagnosis of limiting factors of UR yields (Van Keer et al 1998, Van Keer 2003). An on-farm diagnostic survey, covering an extensive range of UR crop situations, was carried out during 1993-96 in a remote Lahu highland village of Chiang Mai Province, in the western part of upper northern Thailand. The objectives of this crop diagnostic survey were threefold:

(i) To characterize the UR crop population, environmental conditions, and farmers' practices along the whole crop cycle and across several climatic years,
(ii) To date and quantify UR yield differentiation under actual farmers' circumstances and management practices, and
(iii) To identify, date, and rank the main environmental and cropping system variables causing major yield limitations under farmers' circumstances and management practices.

Materials and methods

Data on crop population status were collected for the two early- (95-115 days) and late- (138-177 days) maturing common types of local cultivars. These panicle-weight plant type tropical japonicas were found to be weakly and strongly photoperiod-sensitive for the Chaloina (early) and Chaae (late) varieties, respectively. The crop environmental conditions and cropping practices were monitored every 2 weeks from a total of 432 intra-field monitoring squares (1 m^2 each). These squares were delimited at crop emergence in 63 often-sloping farmers' fields of deep Acrisol soils developed on granite with a clay-loamy texture and medium level of physical and chemical fertility. In the first year, all the selected plots were new fields cleared from three different types of fallow vegetation (grassland, bamboo groves, or young secondary forest). These fields were monitored until they were fallowed again after 1, 2, or 3 years of successive UR monocropping. Additional newly cleared fields were included in the survey during the following 3 years of the survey. As a result, the number of fields surveyed during the 1993, 1994, 1995, and 1996 wet seasons were 12, 14, 19, and 18, respectively.

We applied an interpretative and empirical model of yield buildup to the subset of survey

data on crop population parameters to quantify the upper limits or potential values of the successive UR yield components other than the first one, plant density (Van Keer 2003). The same model also provided an understanding of the relationship between the upper limit of a given yield component and the value achieved by the preceding one. Subsequently, "Phase realization indices," which are the ratios of the yield potential retained at the end of a given phase of the yield buildup process to the yield potential retained at the end of the previous phase, were calculated (Wey et al 1998). These indices synthesize the effects of crop constraints on the functioning of the UR crop population during the successive phases of the UR yield buildup process in each monitoring square. Their distribution patterns were analyzed to assess the relative importance of successive growth and development phases for the determination of UR yields.

To identify and rank causes of rice yield differentiation, a principal component analysis with instrumental variables (PCAIV, Lebreton et al 1991) was carried out on the 1993-96 pooled data, as well as for individual year subdatasets. PCAIV allows, for the same number of individual entities, the simultaneous analysis of two multivariate data matrices, that is, a dependent matrix, made up in this case of UR crop population characteristics (yield and successive components of yield), and an independent matrix comprising all the measured crop environmental and management variables. The statistical procedure contains the following two steps:

(i) First, simultaneous multiple regressions for each variable of the dependent crop population data matrix on all variables of the independent crop environment and management matrix are carried out. After this step, a new matrix is obtained, displaying the part of the crop population characteristics explained by the crop environment and crop management data.

(ii) Then, a classical principal component analysis (PCA) is performed on this new matrix.

In this on-farm agronomic survey, for both pooled data and individual years, relatively high levels were obtained for the percentage of inertia of the first two axes and for the multivariate correlation (ratios) of the PCAIV (Table 2).

The study site

This on-farm diagnostic survey was carried out in Mae Haeng, a highland (600-800 masl) Lahu village in Fang District of Chiang Mai Province. The local agroecosystem is characterized by a strong relief, 2- to 10-year-old heterogeneous (grasslands, bamboo groves, and secondary forest) types of fallow vegetation, and a wide range of weed species, diseases, and insect or other animal pests. Deep (50 to more than 200 cm) humic Acrisols developed on a strongly weathered bedrock of carboniferous granite are the dominant type of soil. The total annual rainfall recorded at the nearby Fang meteorological station varied from 1064 to 1910 mm over 16 years, with an average of 1482 mm. Rainfall distribution follows a slightly bimodal pattern, with frequent dry spells occurring in late June and early July.

Local farming systems are still at an early stage of diversification and integration into the market economy. Crop production is still mainly based on the subsistence cultivation of UR. Farmers grow only local cultivars and the late-maturing non-glutinous ones (the villagers' basic staple) amount to 70-80% of the total UR production. Mae Haeng farmers grow UR according to traditional swidden cultivation practices, with almost no external inputs. Only weed control

practices are gradually diversifying, following the adoption of hoe tillage and the application of salt (NaCl) as an effective herbicide against the local major weeds belonging to the *Asteraceae* family (Van Keer et al 2001).

Results and discussion

Extent of UR yield variability

Figure 1 shows the distributions of grain yields for both early- and late-maturing cultivars. They display an extensive variability of UR productivity at the study site (from 0 to 438 $g.m^{-2}$). Both cultivar types produced low yields in a majority of the monitoring squares, with similar distributions. Average yields were low and only slightly different at 113 and 130 $g.m^{-2}$ for early- and late-maturing cultivars, respectively. The recorded yield maxima were relatively high at 308 and 438 $g.m^{-2}$ for early- and late-maturing cultivars, respectively, and their difference was substantial. Such a situation is favorable for the application of a crop diagnostic approach to explain how such an important variability is produced.

Parameters of the UR yield buildup reference curves for the main local varieties

Data scatters from farmers' UR fields support the existence of such yield buildup reference curves, similar to those already established for other cereal crops. Figure 2 displays such scatters and reference curves for the relationship between plant densities and the number of panicles per plant for both types of UR cultivars under study. Table 1 presents a synthesis of all such parameters of the yield buildup reference curves for both UR cultivars and for all successive phases of the crop cycle. For each phase, three parameters were estimated:

(i) The maximum value of the area-based yield component built up during a given phase,

(ii) The maximum value of the intermediary component built up during each successive phase (number of panicles per plant, number of spikelets per panicle, grain-filling rate, and 1000-grain weight),

(iii) The threshold value for each yield component beyond which competition effects between successive yield components were observed.

These parameters were subsequently used to calculate the phase realization indices for each crop monitoring square to identify and rank the periods of UR yield differentiation.

Dating and ranking the periods of UR yield differentiation

For the reproductive phase of the UR crop cycle, the analysis of the yield buildup processes using the phase realization indices method pinpointed panicle formation and spikelet differentiation as key periods of yield differentiation. Figure 3 shows that only a small number of squares were able to approach the maximum index value of 1 during this phase. This indicates that only these few squares did not experience strong limiting factors during this phase. Such favorable conditions seemed to occur more frequently in fields planted to the early-maturing variety than in plots where the late-maturing cultivar was grown. But, for the vast majority of the squares and both types of cultivars, the yield component buildup process was severely limited during this period. Similar histograms constructed for the other phases of the UR crop cycle show far higher proportions of squares with index values higher than 0.8 and less severe limitations of the yield buildup processes (data not shown).

During the vegetative period, poor crop biomass accumulation was found to be more important than low plant density. Vegetative biomass accumulation per plant influenced panicle and spikelet formation, but neither spikelet fertilization nor grain filling (data not shown).

This stepwise analysis of the variation of UR yields and yield components provided the basis for an on-farm crop diagnosis of UR yields to identify and rank the causes of their limitations.

Identifying and grading the causes of UR yield differentiation

Figure 4 shows the results of the PCAIV statistical analysis of pooled data. This analysis reveals strong negative relationships for

(a) number of panicles plant^{-1} and number of spikelets panicle^{-1} vs rice root aphid infestation,

(b) plant density vs late weed competition and late-maturing cultivars (these cultivars are planted at lower sowing densities), and

(c) percentage of filled spikelets and 1000-grain weight vs 1995 wet season, which was the only rainy season characterized by dry spells occurring during the critical reproductive phase of the UR crop cycle.

Weaker negative relationships were found for number of panicles plant^{-1} vs slope angle, erosion, number of successive UR crops, minimum tillage, and early weed stress. A rather weak positive correlation between the older forest type of fallow and panicles plant^{-1}, number of spikelets panicle^{-1}, and UR grain yield was also observed. Brown spot was the only disease with limited importance, especially for late-maturing varieties.

Table 2 shows the analysis of the major and minor limiting factors of UR yield and its components for individual year subdatasets. These more detailed analyses isolated rice root aphid infestation as the single major limiting factor with a strong and consistent effect on final UR grain yields. Weed competition was found to be the second most important yield-limiting factor (even after the usual farmers' weeding practices performed in the monitoring squares), followed by soil erosion in sloping and shallow-tilled fields.

It was only in one out of four cropping seasons that the last two UR yield components were negatively affected by drought, although the local UR cultivars were not very deep rooting ones. Observations on their rooting patterns showed that their maximum rooting depth was at least 80 cm. However, root mass densities dropped sharply from an average of 1.7 mg cm^{-3} in the topsoil (0-20 cm) to less then 0.1 mg cm^{-3} in the subsoil (20-80 cm). Only about 10% of their total root masses were found below 20-cm depth, while, for typical deep-rooting UR cultivars, the subsoil root fraction usually amounts to 20-40% (Yoshida 1981).

That no very significant fallow effect or soil nutrient-limiting factor was diagnosed could be because the survey was carried out on a soil type with a relatively high level of physical and chemical fertility. It is also possible that the standard static soil fertility measurements used in the survey were not sufficient to identify such relationships with crop population characteristics. The fact that similar weed communities, dominated by the wind-disseminated *Ageratum conyzoides* species, were observed in all the monitored fields also contributed to limit the identification of

fallow-type effects.

Conclusions

The results of this on-farm agronomic survey show that the inherent yield potentials of local UR cultivars grown by farmers are not a major cause of low UR yields at this site. Improvements in UR crop management practices could lead to significant progress in closing the important yield gaps observed for both early- and late-maturing cultivars. Consequently, crop management research should dominate the research agenda for such montane UR-based cropping systems.

We also found that an empirical model of yield buildup processes, associated with the calculation of phase realization indices, can be applied to identify and rank the periods of yield differentiation in UR among farmers' fields. Subsequently, it was possible to identify and grade the main limiting factors to be alleviated during the critical phases of the UR crop cycle. UR yield differentiation was found to occur mainly during (i) biomass accumulation in the vegetative phase and (ii) during the early part of the reproductive phase (panicle and spikelet formation) of the UR crop. Results of this on-farm agronomic survey support the validity of several well-known hypotheses on UR limiting factors, such as weed competition, soil erosion, and drought stress. But, this in-depth study also showed that closer attention should be paid to the management of soil-borne upland rice pests when setting priorities for improving UR-based cropping systems in the northern Thailand highlands.

Such a UR crop diagnosis allows the definition of a precise agenda for designing and evaluating improved cropping systems. This is not an easy task as crop environmental conditions were found to be far more limiting than the current cropping practices performed by farmers. Nevertheless, based on the use of weed-competitive and drought-tolerant cultivars, such innovative cropping systems could include UR in crop rotations for maintaining soil fertility and breaking the biological cycles of soil-borne pests. But, to be attractive to small farmers, such cropping systems should also include less tedious weed control techniques, thus allowing a sharp increase in labor productivity.

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Figure 1. Distribution of grain yields for early- and late-maturing upland rice cultivars in Mae Haeng Village, Chiang Mai Province, Thailand. Pooled data for 1993-96 cropping seasons. χ^2 test of no difference: P = 0.46.

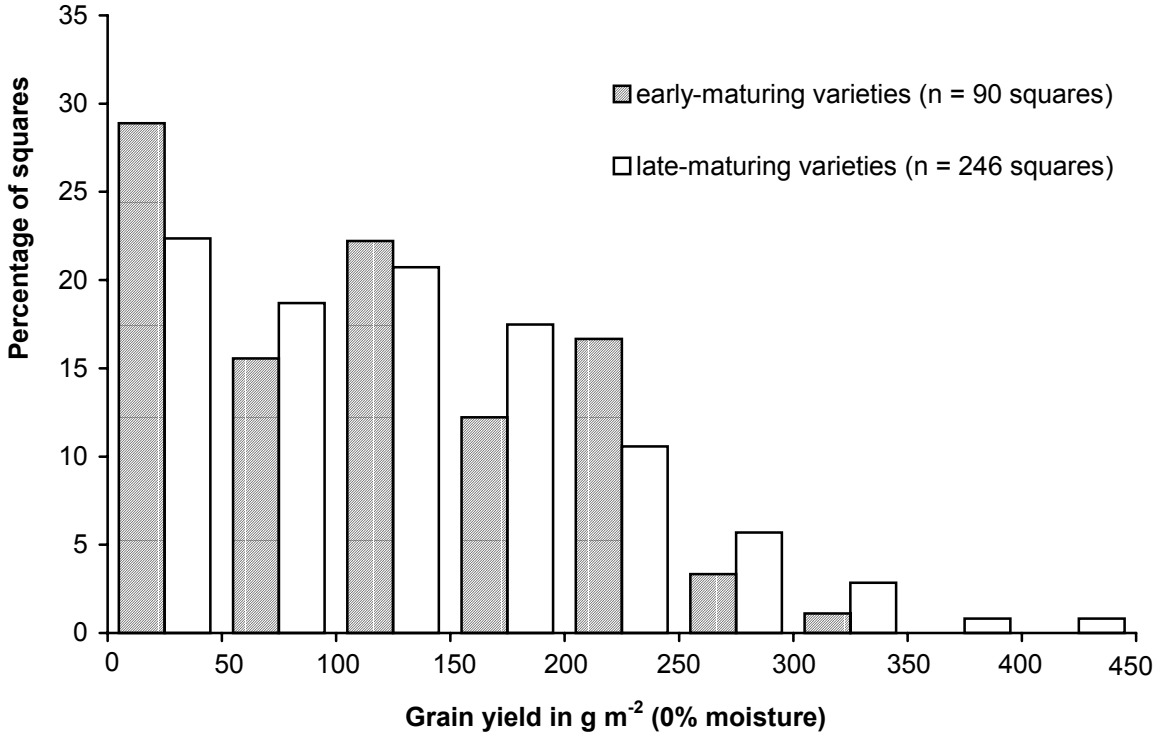
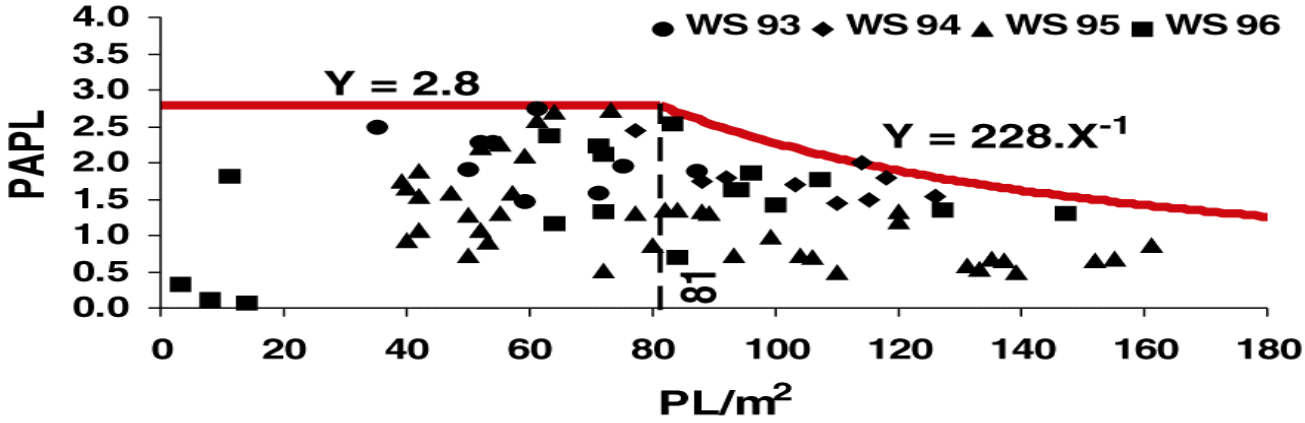


Figure 2. Yield buildup reference curves on relationships between plant density and number of panicles per plant for Chaloina/early- (a) and Chaae/late-maturing (b) upland rice varieties in Mae Haeng, Chiang Mai Province, Thailand. Pooled data for 1993-96 cropping seasons.

(a) Chaloina (n = 78)



(b) Chaae (n = 263)

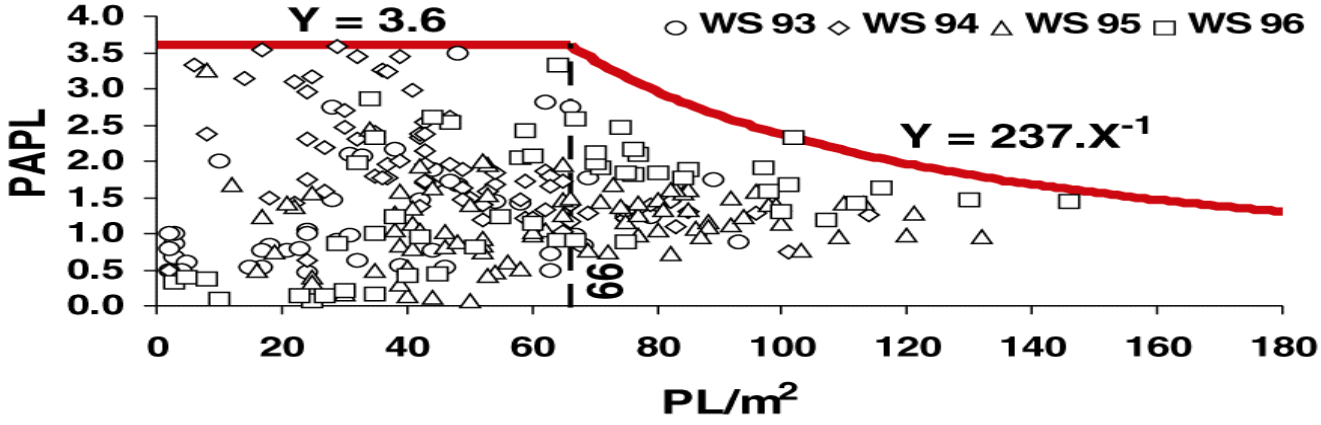


Figure 3. Distribution of the phase realization indices during the period from panicle initiation to flowering for early- (EM) and late- (LM) maturing upland rice cultivars in Mae Haeng, Chiang Mai Province, Thailand. Pooled data for 1993-96 cropping seasons.

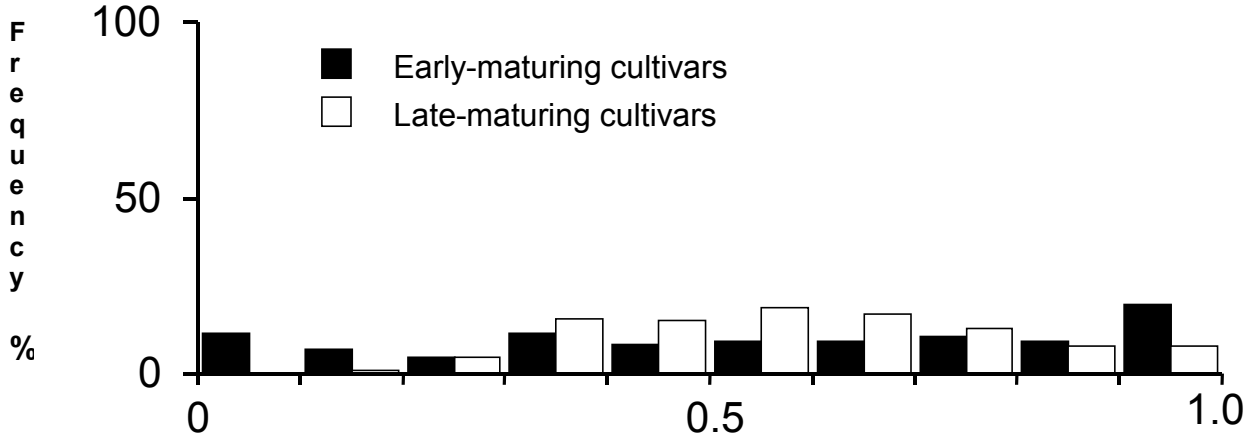


Figure 4. Plane of PCAIV first two axes showing the relationships among upland rice yield, yield components, crop environmental conditions, and crop management practices in Mae Haeng, Chiang Mai Province, Thailand. Pooled data for 1993-96 cropping seasons.

Legend:
Crop growth variables (measured at harvest): PL = no. of plants m^{-2}; PAPL = no. of panicles $plant^{-1}$; SPPA = no. of spikelets $panicle^{-1}$; % FSP = percentage of filled spikelets; WTG = 1000-grain weight; YIELD = grain yield.
Crop environmental and management variables: ec, lc = early, late cultivars; mt, dt = minimum, deeper tillage; yc = no. of successive years of upland rice cultivation; ff, bf, gf = forest, bamboo, grass fallows; ws1, ws2, ws3, ws4 = 1993, 1994, 1995, 1996 wet seasons; sl = slope angle; er = severity of soil erosion; sand = percentage of sand; ph = pH; som = soil organic matter; pav = available P; camg = soil Ca + Mg content; k = soil K content; we1, we2 = cumulated area under the weed cover curve for 0-60 days after sowing (DAS) and for 60 DAS to harvest, respectively; bs = degree of brown spot infestation; ra = degree of rice root aphid infestation.

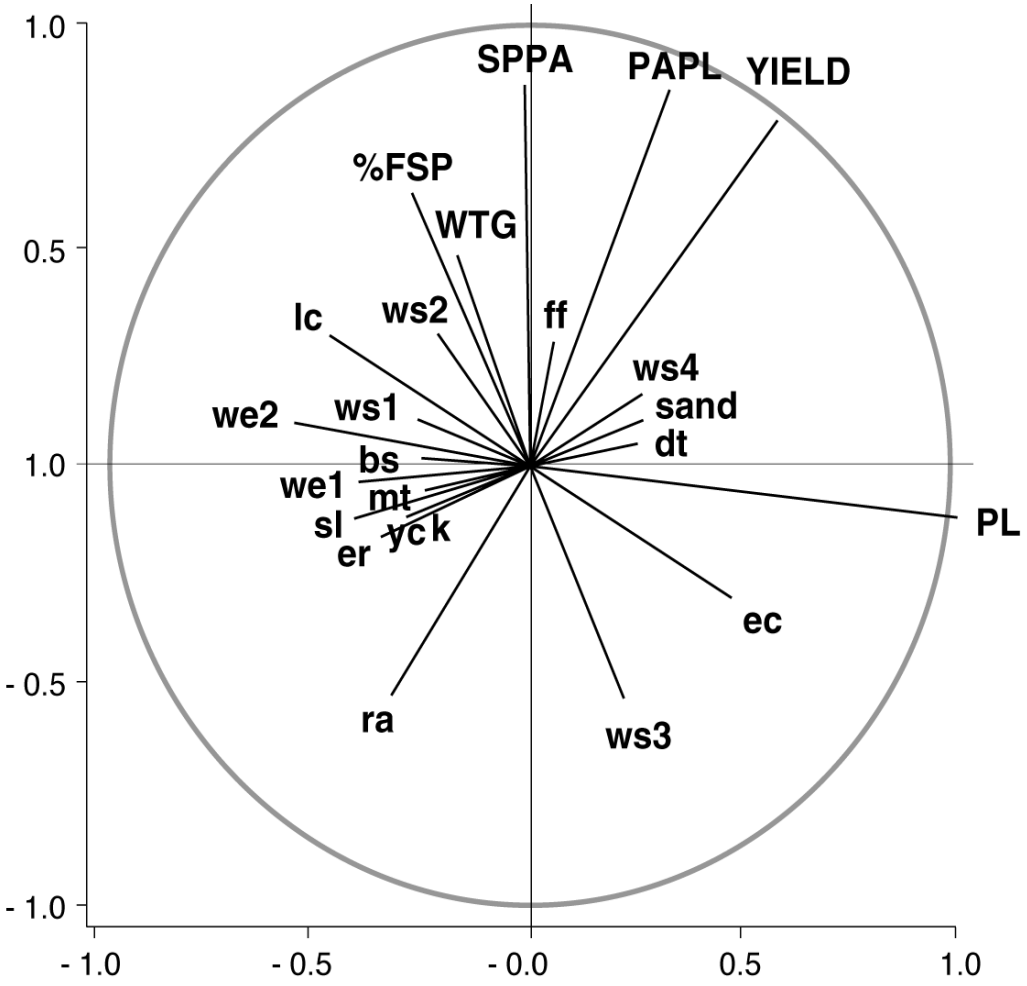


Table 1. Parameters of the yield buildup reference curves for Chaloina/early and Chaae/late upland rice cultivars in Mae Haeng, Chiang Mai Province, Thailand. Pooled data for 1993-96 cropping seasons.

Cultivar	*Chaloina* (Early)	*Chaae* (Late)
Spikelet filling		
Maximum grain yield, GY_{max} (g m^{-2} 0% H_2O)	308	438
Max. 1000-grain weight, WTG_{max} (g 0% H_2O)	23.2	24.3
Threshold for filled spikelets, FSP_{comp} (nb m^{-2})	13,300	18,000
Spikelet fertility		
Max. nb filled spikelets, FSP_{max} (nb m^{-2})	16,200	20,600
Max. grain-filling rate, SFR_{max} (%)	80	96
Threshold for nb of spikelets, SP_{comp} (nb m^{-2})	20,100	21,500
Spikelet formation		
Max. nb of spikelets, SP_{max} (nb m^{-2})	22,100	26,700
Max. nb of spikelets $panicle^{-1}$, $SPPA_{max}$ (nb)	144	183
Threshold for nb of panicles, PA_{comp} (nb m^{-2})	154	146
Panicle formation		
Max. nb of panicles, PA_{max} (nb m^{-2})	228	237
Max. nb of panicles $plant^{-1}$, $PAPL_{max}$ (nb)	2.8	3.6
Threshold for plant density, PL_{comp} (nb m^{-2})	81	66

Table 2. Major and minor factors and conditions influencing upland rice yield buildup based on results of PCAIV analysis for each cropping year in Mae Haeng, Chiang Mai Province, Thailand. Data for 1993-96 crop years. Boldface indicates strongest relationships.[a]

Year	1993 WS		1994 WS		1995 WS		1996 WS		1993-96 WS	
Relationship	-	+	-	+	-	+	-	+	-	+
No. of plants m^{-2}	**lc** er we1, we2 mt, sl	**ec** sa, dt	**we2, lc** we1 yc, ff	ec	**ra**, we2 we1 er, yc		**we1**, we2 camg k, yc lc	ec	**we2** lc	**ec** **dt**
No. of panicles $plant^{-1}$	**ra** we1, we2 camg ph, bf mt, sl, k	sa, dt	**er** k ra, bs camg pav		**ra**, we2 gf er, yc we1		**er** **ra** **sl, mt** camg k, yc	**dt**	**ra** ws3 er,sl we1, ws3 yc, mt	ff
No. of spikelets $panicle^{-1}$	**ra** we1, we2 camg, ph bf, mt, sl	ff	er k ra, bs camg, pav		**ec** gf, lc ra, we2	camg sl	ra mt er		**ra** **ws3** ec, er sl, yc	
% filled spikelets	ec	lc			**ws3** ec, gf	camg lc			**ws3** ec	lc ws2
1,000-grain weight					**ws3** lc, we1	ec			**ws3** ec	lc ws2
Inertia of axes 1-2 (%)	84		87		70		75		84	
Multivariate correlation (%)	63		67		52		79		37	

[a] See Figure 3 for abbreviations of variables.