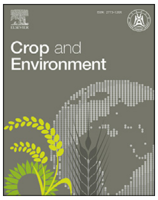
Crop and Environment 1 (2022) 108–114

Contents lists available at ScienceDirect

Crop and Environment

journal homepage: www.journals.elsevier.com/crop-and-environment



Original Article

Performance and adoption of submergence-tolerant TDK1-Sub1 rice in southern Lao PDR

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ARTICLE INFO

Keywords:
Disease
Drought
Farmer perception
Pest
Rainfed lowland

ABSTRACT

Under short-term submergence (7–15 days), submergence-tolerant rice genotypes (e.g. TDK1-Sub1) have been reported to be higher yielding than their intolerant equivalents without the *Sub1* gene. This paper examined whether TDK1-Sub1 was superior to Other locally-preferred genotypes, with and without submergence, using 66 on-farm comparisons in southern Lao PDR. Data were examined for 2 genotype categories (TDK1-Sub1, Other) in 3 environment groups (Favourable, Drought, and Submergence), with 22 farms per group used as replicates. Farmers saved seeds of TDK1-Sub1, planted it again in flood-prone fields, and disseminated its seeds to relatives, neighbours and friends, but they did not do so in areas with lower flood risk. Grain yield was generally higher under Favourable conditions (2.42 t ha^{-1}) than under Submergence (1.94 t ha^{-1}) or Drought (1.90 t ha^{-1}). Under Submergence, the grain yield of TDK1-Sub1 (2.22 t ha^{-1}) was significantly higher than the Other genotype (1.65 t ha^{-1}; $P < 0.10$). Conversely, under Drought, the grain yield of TDK1-Sub1 (1.58 t ha^{-1}) was significantly lower than the Other genotype (2.22 t ha^{-1}; $P < 0.10$). Submergence-tolerant genotypes should enhance system intensification and food security in submergence-prone areas, but yields of other locally-preferred genotypes were more stable in the absence of submergence, especially under late-season drought. Current efforts to introgress additional resistances into submergence-tolerant genotypes are worthwhile, to reduce any downside risk in the absence of flooding. Nevertheless, for Lao PDR and others who prefer glutinous rice, the *Sub1* gene should be introgressed into the best-adapted glutinous rice genotypes, which already possess other resistances.

1. Introduction

Agriculture is at the core of the Lao economy and society, employing 80% of the population and contributing 30% of GDP. Smallholder production is the core element of agricultural and rural development, but is confronted by multiple challenges: traditional low input systems, labour shortages (Manivong et al., 2012) and water stress, including variable and unreliable access to water resources in the dry season (Vote et al., 2015, 2019), flood and drought events in the wet season (Eliste et al., 2012), and variability in onset of the monsoon (Snidvongs et al., 2003). Under rainfed lowland conditions, the intent is to grow the rice crop in standing water in bunded fields, although variable climatic conditions make this difficult to control, so the crop may encounter flood or drought, even in the same season (Fukai and Wade, 2021). These challenges are exacerbated by poverty, poor financial and natural resources, weak infrastructure and institutions, and poor market access. These major limitations experienced at the farm level must be considered in any new techniques and technologies that are tested as options to improve the productivity of the existing wet season rice crop to ensure household food security.

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https://doi.org/10.1016/j.crope.2022.04.001
Received 11 January 2022; Received in revised form 6 April 2022; Accepted 8 April 2022

Crop loss due to submergence in areas that are poorly drained or flooded by overflow from rivers can be considerable, and it is estimated that globally up to 22 million ha of rice is affected annually (Sripongpangkul et al., 2000). While internode elongation to keep panicles above the floodwater is a successful strategy (avoidance) under prolonged and deep submergence, a non-elongation strategy (tolerance) is more successful under short-term submergence of 7–15 days (Ram et al., 2002). The Sub1 gene was identified as a major contributor under short-term submergence (Bailey-Serres et al., 2010), so breeding programs used marker-assisted backcrossing to introgress the *Sub1* gene into eight regionally-preferred genotypes for flood-prone areas in different countries (Ismail et al., 2013).

With the national preference for consumption of glutinous rice (Inthapanya et al., 2006), deployment of the *Sub1* gene in the Lao glutinous-rice genotype Tha Dok Kham 1 (TDK1-Sub1) offered farmers with flood-prone land a risk-management strategy to maintain production intensity. Submergence-tolerant genotypes have out-yielded their equivalent genotype without the *Sub1* gene under short-term submergence, and as a result, they have been widely adopted for flood-prone areas (Mackill et al., 2012). This paper examined whether TDK1-Sub1 was superior to locally-preferred genotypes other than TDK1 alone, under favourable, submergence, and drought conditions. Farmers' responses to the on-farm comparisons were also explored.

2. Materials and methods

2.1. Locations and genotypes used in on-farm comparisons

TDK1-Sub1 and Other genotypes were compared over 100 farms in southern Lao PDR in the 2012 wet season, with farms chosen from Mounlaparmouk, Soukhouma and Phonthong Districts in Champassak (CPK) Province, and Kaysone, Songkhon, Champhone, Asaphangthone and Phalanxai Districts in Savannakhet (SVK) Province. Lowland soils in Lao PDR are predominately sandy in texture, low in pH and available nutrients, and low in water holding capacity (Linquist and Sengxua, 2001). Soils generally had a pH of 4.8, total N 0.06%, available P 3.15 mg kg^{-1}, exchangeable K 18.9 cmol kg^{-1}, and soil organic carbon (SOC) 0.71% (Table 1). Soil pH was higher in Mounlaparmouk (5.5) and Soukhouma (5.1), available P was higher in Champhone (8.3 mg kg^{-1}), exchangeable K was higher in Champhone, Kaysone and Songkhon (34.5 cmol kg^{-1}), and SOC was higher in Mounlaparmouk, Soukhouma and Asaphangthone (1.01%). Details of the 100 farms are in Supplementary Table 1 (Table S1).

Monsoonal rainfall is seasonal, with the wet season generally from May to October, though timing of commencement and cessation, and the amount received, are spatially and temporally variable (Table 2). Long-term temperatures range from 15 °C to 35 °C, with the lowest minimums in December–January, and the highest maximums in March–May. Temperatures followed similar patterns across sites, but CPK in the south was warmer with higher evaporative demand than SVK. Mean annual rainfall was higher in CPK (2044 mm) than in SVK (1452 mm), but in all sites, there was a pronounced dry season from November to March. In 2012, pre-sowing rainfall was above the long-term mean in both provinces, but remained below average thereafter, except in CPK in September 2012, with little rainfall received from October onwards in either province. Growing season rainfall was higher in 2013 in both provinces, but especially in CPK in September 2013.

Genotype TDK1 was originally released by the Agricultural Research Centre in Lao PDR in 1993 as a widely-adapted high-yielding photoperiod-insensitive glutinous-rice genotype, responsive to N and other inputs, and widely grown under irrigated and rainfed lowland conditions (Inthapanya et al., 2006). Following marker-assisted backcrossing to introgress the *Sub1* gene into TDK1 (Bailey-Serres et al., 2010), genotype TDK1-Sub1 was released in 2012 for lands subject to 7–15 days submergence (Mackill et al., 2012). The locally-preferred genotype for comparison was chosen by farmers, and comprised 58 genotypes released by the Lao breeding programs (TDK, PNG, and TSN prefixes) and 42 improved traditional genotypes (Table S1), all of which were classified as Other for the purpose of this analysis.

2.2. Treatments and data collection

Farmers were provided with 20 kg of seeds of TDK1-Sub1, and were asked to compare it with the other genotype (Other) they would usually sow on land likely to be flooded. Following normal practice (Newby et al., 2014), a basal fertilizer dressing (15 kg N ha^{-1}, 5 kg P ha^{-1} and 1.5 kg K ha^{-1}) was generally applied, and seedlings were transplanted in mid to late July, with harvest in late-October to mid-November. Topographic position in each farm was noted (3 = lower, 2 = mid, 1 = upper topography; Wade et al., 1999b), and data were recorded on the depth and duration of each flood, whether the floodwater was clear or turbid, and whether floodwater was stagnant or flowing. Rankings (1 = yes, 2 = no) were also obtained for the occurrence of submergence and drought, and for the incidence of pests or diseases. Mean rank over farms was calculated for each group. Event frequency of ranking variables was evaluated based on their percentage of occurrences (yes), for each event over farms in each group. Grain yields were estimated after air drying, so seeds could be resown, according to the weight of grain obtained from the area harvested, usually 0.10 ha.

2.3. Statistical analysis

Of the 100 on-farm experiments, data from 66 on-farm experiments were retained for statistical analysis, for which all critical parameters were available for both genotype groups (Table S1). Of the 66 environments, 22 farms in which both genotypes encountered complete submergence were allocated to the Submergence group, 22 farms in which both genotypes encountered late-season drought were allocated to the Drought group, and 22 farms in which neither genotype encountered submergence nor drought were allocated to the Favourable group. The remaining 34 farms were excluded from the analysis because: a) The Other genotype was not sown or failed to emerge (2 farms); b) Under

Table 1
Analysis of soils used in on-farm experiments in Lao PDR in 2012 and 2013.

Province	District	Soil pH[a]	Total N[a] (%)	Available P[a] (mg kg^{-1})	Exchangeable K[a] (cmol kg^{-1})	Organic carbon[a] (%)
CPK[b]	Mounlaparmouk	5.5	0.07	1.14	13.0	1.15
	Soukhouma	5.1	0.05	1.37	6.9	0.97
	Phonthong	4.9	0.05	1.58	5.9	0.32
SVK[b]	Kaysone	4.5	0.04	1.13	28.5	0.49
	Songkhon	4.4	0.06	5.12	39.2	0.64
	Champhone	4.8	0.04	8.30	35.7	0.63
	Asaphangthone	4.5	0.07	2.46	11.0	0.91
	Phalanxai	4.8	0.08	4.10	11.0	0.56

[a] Soil pH, 1:1.25; Total nitrogen, Kjeldhal; Available phosphorus, Bray II; Exchangeable potassium, 1 N ammonium acetate; Soil organic carbon, Walkley and Black.
[b] Provinces were Champassak (CPK) and Savannakhet (SVK).

Table 2
Long-term mean monthly maximum and minimum temperature (°C) and pan evaporation (mm), and monthly rainfall (mm) in 2012 and 2013 relative to the long-term mean monthly rainfall, for Savannakhet and Champassak Provinces in southern Lao PDR.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Temp and Evap														Mean
Savannakhet	Tmax	29.3	31.4	33.8	35.0	33.3	32.0	31.3	30.6	31.1	30.5	28.8	27.7	31.2
	Tmin	14.9	17.7	21.3	23.9	24.6	24.8	24.2	24.0	23.5	21.4	17.6	14.7	21.1
	Evap	169	172	191	203	172	151	163	133	139	151	173	184	2002
Champassak	Tmax	31.4	32.9	34.7	35.0	33.2	31.2	30.5	30.2	30.3	30.8	30.6	30.1	31.7
	Tmin	18.2	20.8	23.6	25.2	24.9	24.6	24.2	24.2	23.8	22.7	20.7	18.6	22.6
	Evap	200	217	251	245	211	145	138	129	127	191	198	202	2255
Monthly Rain														Total
Savannakhet	2012	8	1	51	76	203	203	154	223	74	33	9	0	1034
	2013	5	0	74	85	294	239	404	130	370	51	3	19	1674
	Mean	4	17	32	91	168	263	219	343	219	87	7	2	1452
Champassak	2012	44	0	32	81	221	209	286	288	423	14	9	0	1607
	2013	0	0	19	78	204	300	459	460	936	163	12	65	2696
	Mean	2	16	25	75	245	324	434	468	309	116	30	2	2044

flooded conditions, the Other genotype was not fully submerged (6 farms); c) Grain yield data were missing for one or both genotypes (13 farms); d) Grain yield data were out of range (>6.50 t ha^{-1}) (6 farms); or e) Were suitable for the Favourable environment, but no matching data sets were available for Submergence and Drought environments (7 farms).

Analyses of variance were conducted using CropStat (IRRI, 2007) for 2 genotype categories (TDK1-Sub1 and Other) × 3 environment groups (Favourable, Drought and Submergence) × 22 Farms (used as Replicates). Means were compared using appropriate LSD for genotype, environment and their interactions ($P < 0.10$ or $P < 0.05$; Steele and Torrie, 1960). Ranking variables were considered based upon their frequency of occurrence.

While the convention in agronomy is to consider statistical significance at $P < 0.05$, there are precedents for choosing a different level such as $P < 0.10$ (Steel and Torrie, 1960), especially for on-farm participatory experiments, where there are additional challenges of within-field variability as well as site to site and year to year variation (Atlin et al., 2001; Virk et al., 2003). While data precision may be lower, on-farm experiments have advantages, as they sample a wider range of environments, permit farmer perceptions to be evaluated, and are more representative of target environments. Thus, papers reporting on-farm experiments often accept a lower level of statistical significance ($P < 0.10$), whilst retaining statistical rigour in data evaluation (e.g. Sengxua et al., 2018). Accordingly, agronomic traits were generally evaluated at $P < 0.10$ in these on-farm experiments.

2.4. Farm household survey

In a follow-up survey in July 2013, 100 families were interviewed to enable comparison of TDK1-Sub1 and the Other genotype they normally used. The survey captured household characteristics, details of crop management and performance, and the incidence and intensity of flooding and other limitations experienced. Farmers reported on the numbers of floods they had encountered on their flood-prone land in the last 5 years, and their perceptions of TDK1-Sub1 compared with their usual genotypes. Farmers were also asked if they would plant TDK1-Sub1 again, and whether they would share seeds of TDK1-Sub1 with other farmers. If they were not satisfied with TDK1-Sub1, they were asked why not. If they intended to share seeds of TDK1-Sub1, they were asked to whom they would pass seeds of TDK1-Sub1 for the next wet season. The farmer perception data were examined using chi-squared (X^2) with appropriate degrees of freedom, based on their frequency of occurrence (Steel and Torrie, 1960).

3. Results

Among the 22 farms at which submergence was observed, all 22 farms in the submergence group had at least one flood, 16 of them had two floods, and 7 of them had three floods (Table 3). Mean depths of flooding over the three cycles were 1.90, 2.01 and 1.58 m, with mean durations of 7.96, 7.60, and 6.80 days, respectively. Floodwater was always turbid (100.0% of farms) and generally flowing (88.9% of farms) (Table 3). In the drought environments, all 22 farms encountered late-season drought, while 11.4% of farms in the submergence group also encountered mild drought, but only late in the growing season after submergence (Table 4). In contrast, the 22 farms in the favourable environments encountered neither submergence nor drought. The topographic positions of Drought (1.93) environments were generally higher than those of Favourable (2.43) and Submergence (2.36) environments (Table 4). Pests were often present (58.3% of farms), especially under Favourable and Submergence conditions, while diseases were less common (15.2% of farms), especially under Drought (Table 4).

Under Favourable conditions, TDK1-Sub1 and Other genotype did not differ significantly in grain yield (2.61 and 2.22 t ha^{-1}, respectively; n.s.; Table 4). Under submergence, however, grain yield of TDK1-Sub1 (2.22 t ha^{-1}) was significantly higher than that of the Other genotype (1.65 t ha^{-1}; $P < 0.10$). Conversely, under drought, grain yield of TDK1-Sub1 (1.58 t ha^{-1}) was significantly lower than that of the Other genotype (2.22 t ha^{-1}; $P < 0.10$).

In the wet season of 2013, there was a significant association between farmers who had planted TDK1-Sub1 again and the number of years with flooding they had experienced previously ($X^2 = 12.7$; $P < 0.05$; Table 5). When the sum of farmers by years of flooding were compared for the two groups (Table 5), farmers who planted again had almost double the incidence of flooding (185 flood-years) compared with farmers who did

Table 3
Characteristics of flooding at 22 farms in southern Lao PDR in 2012. For each flood, data are presented on the number of farms affected, the mean depth (m), and duration (days) of flooding, whether floodwater was turbid or clear, and whether flowing or stagnant.

Flood number in season	Number of farms affected	Flood depth (m)	Flood duration (days)	Water turbidity (%)	Water flowing (%)
1	22	1.90	7.96	100	100.0
2	16	2.01	7.60	100	80.0
3	7	1.58	6.80	100	76.7
Mean		1.89	7.65	100	88.9

Table 4

Grain yield (t ha^{-1}), topographic position, and event frequency for flood, submergence, drought, pest and disease are presented for 2 rice genotypes (TDK1-Sub1 and Other) grown in 3 environments (Favourable, Drought, Submergence) and 22 farms per environment (as replicates) in southern Lao PDR in the 2012 wet season. For each variable, the mean and interaction LSD are shown at the base of the column ($P < 0.10$)[c].

	Grain yield (t ha^{-1})	Topographic[a] position	Flood[b] (%)	Submergence[b] (%)	Drought[b] (%)	Pest[b] (%)	Disease[b] (%)
Environments (E)							
Favourable	2.42 a	2.43 a	0.0 b	0.0 b	0.0 b	59.1 a	18.2 a
Drought	1.90 a	1.93 a	0.0 b	0.0 b	100.0 a	45.5 b	9.1 b
Submergence	1.94 a	2.36 a	100.0 a	100.0 a	11.4 b	61.4 a	18.2 a
Genotypes (G)							
TDK1-Sub1	2.14 a	2.38 a	33.3 a	33.3 a	37.9 a	59.1 a	16.6 a
Other	2.03 a	2.10 a	33.3 a	33.3 a	36.4 a	57.5 a	13.6 a
Interactions (GxE)							
Favourable							
TDK1-Sub1	2.61 a	2.68 a	0.0 b	0.0 b	0.0 b	63.6 a	18.2 a
Other	2.22 a	2.18 ab	0.0 b	0.0 b	0.0 b	54.5 b	18.2 a
Drought							
TDK1-Sub1	1.58 b	1.91 b	0.0 b	0.0 b	100.0 a	45.5 c	13.6 a
Other	2.22 a	1.95 b	0.0 b	0.0 b	100.0 a	45.5 c	4.5 b
Submergence							
TDK1-Sub1	2.22 a	2.55 a	100.0 a	100.0 a	13.6 b	59.1 ab	18.2 a
Other	1.65 b	2.18 ab	100.0 a	100.0 a	9.1 b	63.6 a	18.2 a
Mean	2.08	2.24	33.3	33.3	37.1	58.3	15.2
LSD	0.56	0.63	69.4	69.4	48.4	7.4	9.0

[a] Topographic position was ranked 3 = lower, 2 = mid, 1 = upper topography for each farm. Mean rank over farms is shown here for each group and total.

[b] Event frequency was ranked for individual farms, with 1 = yes, 2 = no. Event frequency is the percentage of occurrences (yes) of each event over farms.

[c] Within each column, values followed by the same small letter do not differ significantly, according to the interaction LSD ($P < 0.10$).

Table 5

The number of farmers planting TDK1-Sub1 again (Yes) or not planting it again (No), relative to the number of flood years they encountered in the previous five years. Their total numbers of floods are shown in parentheses for each group and overall.

	Number of years with flooding in previous 5 years						
Replanted	0	1	2	3	4	5	Total
Yes	3 (0)	15 (15)	5 (10)	5 (15)	15 (60)	17 (85)	60 (185)
No	4 (0)	8 (8)	13 (26)	4 (12)	5 (20)	6 (30)	40 (96)
Total	7 (0)	23 (23)	18 (36)	9 (27)	20 (80)	23 (115)	100 (281)

not plant again (96 flood-years). Of the 40 farmers who did not plant TDK1-Sub1 again, biophysical limitations (25 farms) were more frequently mentioned (Table 6). These included not keeping seeds of TDK1-Sub1 separate (9 farms), having a low yield of TDK1-Sub1 so limited seed was available (5 farms), having limited flood-prone land (7 farms), not normally growing rice in lower topographic positions due to higher flood risk (3 farms), and susceptibility of TDK1-Sub1 to disease (1 farm). Socio-economic reasons (12 farms) for not planting TDK1-Sub1 again included not planting rice again due to lack of labour (6 farms), poor eating quality of TDK1-Sub1 (5 farms), and low price of rice in the market (1 farm). Three farmers did not provide a reason for not planting TDK1-Sub1 again (Table 6).

Table 6

Reasons given by 40 farmers for not planting TDK1-Sub1 again.

Reasons given by farmers	Number
Biophysical reasons	
Not keeping seed of TDK1-Sub1 separate	9
Low yield of TDK1-Sub1, so limited seed was available	5
Having limited flood-prone land	7
Not normally growing rice in lower positions due to higher flood risk	3
Susceptibility of TDK1-Sub1 to diseases	1
Subtotal	25
Socio-economic Reasons	
Poor eating quality of TDK1-Sub1 (and of TDK1)	5
Not planting again due to lack of labour	6
Low price of rice in the market	1
Subtotal	12
No reasons provided	
Subtotal	3
Total	40

In the wet season of 2013, 60 farmers (60%) surveyed had planted TDK1-Sub1 again on about 19 ha of land, and 28 farmers (28%) had already shared seeds with a further 70 households (Table 7). Not surprisingly, there was a significant correlation between farmers who had planted TDK1-Sub1 again themselves, and those who had shared seeds with others ($X^2 = 13.9$; $P < 0.01$). Farmers who planted again and shared seeds did so with two other households on average. Almost all seeds were shared within the village, with farmers sharing seeds with relatives (5 farms), neighbours (2 farms), friends (1 farm), and others within the village (6 farms).

4. Discussion

4.1. Environmental conditions

In the 2012 wet season, flooding was common, especially in SVK Province, and frequency of flooding was positively correlated with topographic position ($r = 0.54$; $P < 0.05$), indicating that flooding was more severe in lower topographic positions (Table 4), where the depth

Table 7

The numbers of farmers planting TDK1-Sub1 again (Yes) or not planting it again (No), and whether they planned to share (Yes) or did not plan to share (No) seed of TDK1-Sub1. In each case, the numbers of farmers who shared or planned to share seed, and the numbers of households with whom they had already shared seed of TDK1-Sub1, are shown.

Replanted		Planned to share	Shared already
Yes (60)	No	35	7
	Yes	25	58
	Sub-Total	60	65
No (40)	No	37	0
	Yes	3	5
	Sub-Total	40	5
Total (100)		100	70

and duration of flooding was greater. On average, the mean duration of flooding over all environments was 7.65 days, which reduced grain yield by 0.48 t ha^{-1} or 19.8% (Table 4). Significant yield reduction under flash flooding is common with submergence durations of 7–15 days (Bailey-Serres et al., 2010), for which the *Sub1* gene has been shown to be of benefit. A non-elongation strategy under short-term submergence, as provided by the *Sub1* gene, allows assimilate reserves to be used for maintenance respiration rather than inefficient growth respiration under anaerobic conditions (Ram et al., 2002). Consequently, some assimilate reserves may still be available as floodwater declines after short-term submergence, so efficient growth can resume *via* aerobic respiration when oxygen is available again. Subject to conditions later in the life cycle, this post-submergence recovery can be expressed as higher grain yield (Table 4), and associated increases in final dry matter and yield components such as grain number (Ram et al., 2002).

While flood duration was often relatively short here (7.65 days on average), its impact on grain yield was still important, because the floodwater was turbid (100% of cases) and usually flowing (88.9% of cases). Turbidity limits entry of sunlight into the floodwater, limiting the opportunity for photosynthesis to meet current assimilate demand (Ram et al., 2002). When floodwater subsides, a silty residue remains on the photosynthetic surfaces, so recovery after submergence is also delayed. With flowing water (flash flood), mechanical damage to the plant may be greater, again impeding recovery (Wade et al., 1999a). If submergence is not complete, however, damage may be reduced, as oxygen may be transported to lower leaves, stems and roots via aerenchyma (Ram et al., 2002), so farms with flooding in which both genotypes were not fully submerged were excluded from the analysis (Table S1).

Late-season drought was also important, with a mean reduction in grain yield of 0.52 t ha^{-1} or 21.5% (Table 5). Frequency of drought was negatively correlated with topographic position ($r = -0.40$; $P < 0.05$), indicating that drought was more severe in upper topographic positions (Table 4), where soils are generally lighter in texture, and there is limited opportunity to benefit from runoff or seepage (Wade et al., 1999b).

Pests and diseases are not generally regarded as major constraints to rice yield in rainfed lowland areas (Douangboupha et al., 2006; Savary et al., 2000). While pests were often present (58.3% of farms; Table 5), they were more common in favourable and submergence conditions, but less common under drought conditions ($r = 0.38$; $P < 0.05$; Supplementary Fig. 1). Thrips can be quite common in rainfed lowland, but generally cause little damage to grain yield. In contrast, gall midge can be a very damaging pest in rainfed lowland, if conditions are dry early in the growing period. Conversely, rice bug and green vegetable bug are more prevalent later in the growing season. Under more favourable conditions, however, pest damage is expected to be much greater, due to very destructive pests such as brown planthopper and green leafhopper, which can devastate rice crops (Douangboupha et al., 2006; Savary et al., 2000).

Diseases were less common (15.2% of farms; Supplementary Fig. 1), but also decreased under drought, especially in the Other genotype (4.5%). Rice blast (*Macroporte grisea*) and brown spot (*Bipolaris oryzae*) are the diseases most commonly observed in rainfed lowland in southern Laos (Douangboupha et al., 2006). Both of these diseases are generally favoured when soils are low in exchangeable K, and limited fertilizer K was applied (Savary et al., 2000), as was the case here. Rice blast is also favoured by higher levels of available N (Savary et al., 2000), so its prevalence is likely to increase under favourable conditions. Again, disease incidence is expected to be much greater under more favourable conditions, with rice blast capable of devastating susceptible crops.

These pests and diseases were observed to be present in these on-farm experiments, but unfortunately, no attempt was made to quantify their individual presence or impact. Hence the conclusion here is merely that pests and diseases were more severe under favourable and submergence conditions, but less severe under drought conditions.

4.2. Differential genotype responses to environmental conditions

TDK1-Sub1 significantly out-yielded the Other genotype under submergence in these on-farm comparisons ($P < 0.10$; Supplementary Fig. 2), which was consistent with reports that the *Sub1* gene conferred a yield advantage under short-term submergence (Ismail et al., 2013; Mackill et al., 2012). Conversely, the Other genotype significantly out-yielded TDK1-Sub1 under late-season drought ($P < 0.10$; Supplementary Fig. 2). This suggests the Other genotypes were better adapted to local soil conditions, were shorter in duration to escape late-season drought, or had other drought adaptations (Appa Rao et al., 2006). TDK1 is reputed to be higher yielding and more responsive to inputs (Inthapanya et al., 2006), so it is perhaps not surprising that TDK1-Sub1 tended to out-yield the Other genotype under favourable conditions here, though the difference was not statistically significant (Supplementary Fig. 2). In this situation, the Other genotype failed to respond to more favourable conditions, which was consistent with their more stable responses over environments (Appa Rao et al., 2006).

Nevertheless, the lower grain yields under favourable conditions in these on-farm experiments, relative to other reports, may be due to the lower fertilizer applications routinely used by farmers (15 kg N ha^{-1}, 5 kg P ha^{-1} and 1.5 kg K ha^{-1}), which are much lower than those commonly recommended here (60 kg N ha^{-1}, 8–26 kg P ha^{-1}, and 25 K ha^{-1}) (Fukai and Ouk, 2012; Haefele et al., 2010; Linquist and Sengxua, 2001, 2003). Alternatively, the prevalence of pests and diseases could also have contributed to lower grain yields under favourable conditions here (Supplementary Fig. 1). Integrated approaches can offer further benefits, such as banding fertilizer with seed for greater seedling vigour, reduced weed competition and higher grain yields (Sengxua et al., 2019). Recently, Sengxua et al. (2022) proposed a strategy for incremental increase in fine-fraction soil organic carbon in order to retain nutrients and water in the root zone of these coarse-textured soils, which should result in a higher yield potential.

4.3. Adoption of TDK1-Sub1 by farmers

The survey results indicated that some farmers were willing to plant rice lower in the topography than they would normally, in order to assess if TDK1-Sub1 was better than their locally-preferred genotype there. This demonstrates two important criteria for farmers in testing new technologies: its relative advantage compared to the practice or technology it supercedes, and the ease with which a farmer can trial it to learn about performance and management skills (trialability) (Pannell et al., 2006). Given the higher grain yield of TDK1-Sub1 under submergence (Supplementary Fig. 2), farmers adopted TDK1-Sub1 when they had land at risk of flooding, but not otherwise (Table 5). This suggests farmers appreciated the likely benefits of growing the submergence-tolerant genotype TDK1-Sub1 on their submergence-prone land, but retained their locally-preferred genotype when submergence was less likely, as the Other genotype was more stable in grain yield, especially under late-season drought (Supplementary Fig. 2). Farmers who did not replant TDK1-Sub1 did so for a range of reasons (Table 6), only one of which was related to performance under submergence. The responses demonstrated that farmers considered all aspects in making decisions, including grain quality, disease resistance, labour availability, and market prospects. This implies that farmers would prefer an adapted glutinous rice genotype of good eating quality (better than TDK1-Sub1), with the *Sub1* gene for submergence tolerance, and with other resistances to drought, pests and diseases also present. Nevertheless, farmers who planted TDK1-Sub1 again also passed its seed on to other family members, neighbours and friends in the village (Table 7). This shows the importance of family-level and village-level networks for out-scaling of new information and technologies, but also the challenge of how to get the information out to neighbouring and more distant villages. In order to be adopted more widely, access to information and resources (seed, machinery, and inputs) is vital, and local government departments, local businesses, NGOs, and community groups should be included in promoting technologies for adoption. Likewise, cross-village visits by farmers should also be promoted, in order to encourage farmer knowledge sharing with successful farmers across villages, with subsequent local technology evaluation and discussion in local villages (Clarke et al., 2018).

These results suggest that TDK1-Sub1 can be a good choice for submergence-prone land, allowing intensification of farming systems in lower topographic positions, thereby improving household food security. Adoption has progressed, with TDK1-Sub1 released as XBF1 (Xe Bang Fai 1) in Lao PDR (Inthapanya et al., 2013), and with XBF1 still being grown by farmers in flood-prone areas of SVK and CPK provinces five years later (Wade and Sengxua, 2019). In areas with a lower risk of flooding, however, other locally-preferred genotypes with more stable yield over environments are a less risky alternative, particularly in upper toposequences which are more prone to drought conditions. Current efforts to introgress further resistances into TDK1-Sub1 and other regionally-preferred genotypes (Mackill et al., 2012) should allow improved submergence-tolerant genotypes to be planted more widely when they become available, with less downside risk in the absence of submergence. Nevertheless, the need remains for the *Sub1* gene to be introgressed into the best-adapted genotypes for rainfed lowland in Lao PDR, such as VT450-2 or TSN9 (Sengxua et al., 2017), which already possess broad adaptation, yield stability, other resistances, better eating quality, and preferably glutinous grain type. Introgressing a single gene (*Sub1*) into such adapted backgrounds should be easier and cheaper than pyramiding multiple traits, e.g. drought, pest and disease resistance.

5. Conclusions

Farmers saved seeds of TDK1-Sub1, planted it again in flood-prone fields, and disseminated its seeds to relatives, neighbours and friends, but they did not do so in areas with lower flood risk. Pests were more common under Favourable (59.1% of farms) and Submergence (61.4% of farms), but less common under Drought (45.5%). Diseases were less common, again with more under Favourable and Submergence (18.2% of farms), but less under Drought (9.1% of farms), especially in the Other genotype (4.5% of farms). Grain yield was generally higher under Favourable conditions (2.42 t ha^{-1}) than under Submergence (1.94 t ha^{-1}) or Drought (1.90 t ha^{-1}). Under Submergence, the grain yield of TDK1-Sub1 (2.22 t ha^{-1}) was significantly higher than the Other genotype (1.65 t ha^{-1}; $P < 0.10$). Conversely, under Drought, the grain yield of TDK1-Sub1 (1.58 t ha^{-1}) was significantly lower than the Other genotype (2.22 t ha^{-1}; $P < 0.10$). Submergence-tolerant genotypes should enhance system intensification and food security in submergence-prone areas, but yields of other locally-preferred genotypes were more stable in the absence of submergence, especially under late-season drought. Current efforts to introgress additional resistances into submergence-tolerant genotypes are worthwhile, to reduce any downside risk in the absence of flooding. Nevertheless, for Lao PDR and others who prefer glutinous rice, the *Sub1* gene should be introgressed into the best-adapted glutinous-rice genotypes, which already possess other resistances.

Declaration of competing interest

The author declares that he/she have no competing interests. Author L.J. Wade (Editorial Board member) was not involved in the journal's review nor in decisions related to this manuscript.

Acknowledgements

This work was supported by the Australian Centre for International Agricultural Research (ACIAR) under Grant number CSE/2009/004, Developing Improved Farming and Marketing Systems in Rainfed Regions of Southern Lao PDR. We thank the 100 farmers from southern Lao PDR, local extension staff for support in data collection, and Provincial and District Governments in Savannakhet and Champassak for allowing their participation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crope.2022.04.001.

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