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Integrated pest management for yard-long bean (*Vigna unguiculata* subsp. *Sesquipedalis*) in Cambodia

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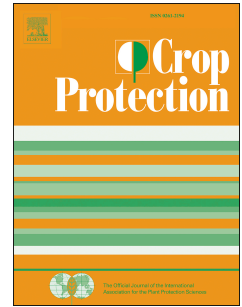
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# Accepted Manuscript

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1 **Integrated pest management for yard-long bean (*Vigna unguiculata***  
2 **subsp. *sesquipedalis*) in Cambodia**

3

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5

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12

13

14 **Abstract**

15 Pesticides are widely used to protect crops against insect pests and diseases. However, current  
16 conventional pest management strategies can severely impact environmental and human health.  
17 Therefore, it is timely to find an alternative to conventional chemical control in order to  
18 counteract the negative effects of pesticides. Integrated Pest Management (IPM) represents a  
19 promising alternative in vegetable production to reduce pesticide use while also maintaining  
20 acceptable yields. In this study, we compared an IPM strategy with conventional management and  
21 a no-spray control for managing arthropod pests and pathogens in yard-long bean (*Vigna*  
22 *unquiculata* subsp. *sesquipedalis*), an important crop in Southeast Asia. We conducted the study  
23 during two crop cycles (rainy and dry season) on 24 farms (12 per season) spread across the Sout  
24 Nikum district of Siem Reap, Cambodia. In both seasons, our IPM strategy controlled overall pest  
25 levels better than conventional pest management, which exhibited better pest control than the  
26 no-spray control. This pattern was not reflected by yields, however, since dry season yields were  
27 similar across all three treatments (conventional = 1.68, IPM = 1.73, control = 1.52 kg m<sup>-2</sup>), and  
28 rainy season yields were similar between conventional and IPM treatments, which were higher  
29 than yields in the no-spray control treatment (conventional = 1.74, IPM = 1.71, no-spray control =  
30 1.33 kg m<sup>-2</sup>). The costs of IPM were higher than conventional management, which contributed to  
31 lower profits in the IPM treatments in both seasons despite yields being as high as in conventional  
32 production. Therefore, future efforts should focus on increasing the profitability of IPM  
33 production.

34

35 **Keywords:** IPM; on farm trial; *Bacillus subtilis*; *Bacillus thuringiensis*; *Beauveria bassiana*;  
36 *Trichoderma*

37

## 38 Highlights

- 39 • IPM outperformed conventional pest management on yard-long bean in Cambodia
- 40 • Pest management strategy did not influence yard-long bean yields
- 41 • Costs for IPM were higher than for conventional management

## 43 1. Introduction

44  
45 Agricultural pests, including arthropods, diseases, and weeds can lead to complete crop  
46 failures (Matson et al., 1997). Over the past century, farmers have increasingly turned to chemical  
47 pesticides to help control pest problems. In fact, the use of chemical pesticides has quickly  
48 become widespread worldwide and it is estimated that 35 billion kg of pesticides are applied  
49 annually (FAOSTAT, 2014). However, it is also estimated that pests still cause the loss of 37% of  
50 potential crop yield (Pimentel, 2005). Pesticides can also have many negative side effects  
51 including: human health impacts, water contamination, killing of non-target species, residues in  
52 food, and the onset of pesticide resistance (Carvalho, 2006; Chagnon et al., 2015).

53 Integrated Pest Management (IPM) provides a potential alternative to conventional pest  
54 management. It was originally introduced as “applied pest control which combines and integrates  
55 biological and chemical control” (Stern et al., 1959). During the last 60 years, IPM has garnered a  
56 great deal of research attention, and we now have a strong foundational knowledge of how to  
57 implement it for most major crops (Way and van Emden, 2000). We still lack sufficient knowledge,  
58 however, of IPM in minor crops. Furthermore, IPM needs to be continuously studied and tailored  
59 to specific situations, which can be a major obstacle to implementing IPM in developing countries  
60 (Parsa et al., 2014). Another barrier to the spread of IPM in developing countries is that

61 conventional pesticides are perceived as a solid investment to protect crops and guarantee  
62 production (Timprasert et al., 2014).

63 In Cambodia, agricultural production plays a pivotal role in the economy and in ensuring  
64 food security. Indeed, 80% of the population lives in rural areas, and the land dedicated to  
65 agriculture is estimated to be 5.5 million hectares (FAOSTAT, 2014), or about one third of the  
66 country. Although policy makers are pushing towards the implementation of IPM in the field,  
67 conventional pest management is still widespread along with the associated negative impacts on  
68 environmental and human health (Jensen et al., 2011). Examples of IPM strategies implemented in  
69 Cambodia are also nearly absent from the scientific literature. For example, a former meta-  
70 analysis by Pretty and Bharucha (2015), spanning 85 IPM projects over 24 developing countries,  
71 reports just one example for Cambodia (Van den Berg and Jiggins, 2007).

72 The current challenge is to develop successful IPM strategies tailored to Cambodia's diet  
73 and growing conditions. *V. unguiculata* subsp. *sesquipedalis* Verdc. (yard-long bean) is one of the  
74 most important legumes for human food consumption cultivated in Cambodia (Tantasawat et al.,  
75 2010). This species can be grown year-round, and the long pods can be collected many times per  
76 crop cycle (Kongjaimun et al., 2012). Insects and diseases, however, pose a major challenge to  
77 successful yard-long bean cultivation. In a survey of farmers in Thailand and Vietnam, leaf rust  
78 (*Uromyces vignae*) and bean pod borer (*Maruca vitrata*) were consistently ranked as the top  
79 disease and insect pest, respectively (Schreinemachers et al., 2014). Other insect pests were more  
80 variable between Thailand and Vietnam with armyworm (*Spodoptera litura*), bean butterfly  
81 (*Lampides boeticus*) and the American bollworm (*Helicoverpa armigera*) being major insect pests  
82 in Vietnam while aphids (*Aphis craccivora* and *Aphis glycines*) were more important in Thailand.  
83 For diseases, leaf spot, root rot, and yellow mosaic virus were major challenges in Vietnam, while  
84 damping off was more important in Thailand (Schreinemachers et al., 2014).

85 Due to the importance of yard-long bean as a staple food in Southeast Asia and Cambodia,  
86 and with the aim to favor the implementation of IPM to counteract the negative effects of  
87 pesticide overuse, we evaluated the use of IPM strategies to protect yard-long bean against both  
88 its major arthropod pests and pathogens. In this research, we took an “IPM package” approach  
89 whereby we tested a suite of management strategies simultaneously (Dinakaran et al., 2013).  
90 Specifically, we focused on the substitution of conventional pesticides with biocontrol agents  
91 targeting insects (*Beauveria bassiana*, *Bacillus thuringiensis*) and diseases (*Bacillus subtilis*,  
92 *Trichoderma viride* and *Trichoderma harzianum*), and products of natural origin (orange essential  
93 oil). These products have been shown to be effective in controlling agricultural pests while being  
94 safe for mammals, having low toxicity for natural enemies or non-target species, and having an  
95 overall low environmental impact (Amin et al., 2010; de Boer Sietske and Diderichsen, 1991; Koul  
96 et al., 2008; Siegel, 2001; Srinivasan et al., 2019; Zimmermann, 2007). We specifically did not use  
97 neem in our IPM package because its use as a pesticide would compete with human consumption  
98 in Cambodia (Seng, pers. comm.). We hypothesized that our IPM strategy could control arthropod  
99 pests and pathogens in yard-long bean at least as well as conventional management.

100

## 101 **2. Materials and methods**

102

### 103 *2.1 Experimental design*

104

105 The study was carried out over a rainy and dry season in the Soutr Nikum district of Siem  
106 Reap, Cambodia. This area is flat with a sandy loam soil (pH 4.2–5.9). During the rainy season (July  
107 2017 – November 2017), the total rainfall was 1,200 mm, with the temperatures ranging from 27  
108 to 33°C with 45-76% relative humidity. During the dry season (November 2017 – March 2018), the

109 total rainfall was 230 mm, with the temperatures ranging from 24 to 33°C with 35-62% relative  
110 humidity.

111

112

113 The research was designed with farmers using a farming systems research approach that  
114 emphasized participatory, on-farm research (Darnhofer et al., 2012; Norton et al., 1999). During  
115 each season, we established on-farm trials at 12 unique sites (24 farms total). Each farm was  
116 considered one experimental replicate and contained two treatments for pest control of yard-long  
117 bean: IPM, and conventional farmer practices. While the IPM treatment protocol was  
118 standardized across farms, the conventional treatment included a mix of farm practices; each  
119 farmer managed their conventional plot according to their usual practices (Dinakaran et al., 2013).  
120 There was also a small, no-spray control area on each farm that was not treated with any  
121 pesticides and that served as a check for pest pressures. Each farm devoted around 300m<sup>2</sup> to the  
122 experiment, with treatments encompassing entire rows of production and treatments separated  
123 only by the regular inter-row space with an approximate ratio of the treatment areas of 3:3:1, IPM  
124 to conventional to no-spray control, respectively. The locations of the IPM and conventional  
125 management treatments were randomized within the experimental area and the no-spray control  
126 was always an outside row. While the relatively small size or placement of the no-spray control  
127 could bias results in that treatment, its placement was decided in conjunction with farmers in  
128 order to minimize spray drift and farmers accidentally spraying those plots (Bingen and Gibbon  
129 2012).

130

131 *2.2 Agronomy*

132

133 Field plots were prepared about two weeks before transplanting by roughly ploughing the  
134 soil before the application of compost/manure ( $5 \text{ t ha}^{-1}$ ) and lime ( $320 \text{ kg ha}^{-1}$ ). Soil was then  
135 ploughed a second time, and hilled ( $80 \text{ cm wide} \times 30 \text{ cm high}$ ) with a  $70 \text{ cm}$  walkway between  
136 rows. Before transplanting seedlings, the drip irrigation system was placed lengthwise in the  
137 middle of each bed and covered with silver plastic mulch. Yard-long bean seedlings were  
138 transplanted one week after seeding and were planted at  $10 \text{ cm}$  of depth with  $30 \text{ cm}$  between  
139 plants within the same row ( $4.76 \text{ plants/m}^2$ ). Plants were grown vertically on a two meter high  
140 trellising system of nets supported by small bamboo or wooden poles, and irrigated daily  
141 according to crop needs. In the rainy season, fields were fertilized with  $50 \text{ kg ha}^{-1} \text{ N}$ ,  $40 \text{ kg ha}^{-1} \text{ P}$ ,  
142 and  $80 \text{ kg ha}^{-1} \text{ K}$ , and during the dry season with  $45 \text{ kg ha}^{-1} \text{ N}$ ,  $45 \text{ kg ha}^{-1} \text{ P}$ , and  $220 \text{ kg ha}^{-1} \text{ K}$ .  
143 Fertilization was divided between a basal fertilizer application during the first plow, which  
144 included 40% of total N and P and 19% of total K during the rainy season, and 44% of total N and P  
145 and 7% of total K during the dry season, with the remaining fertilizer applied as weekly fertigation  
146 applications.

147

### 148 2.3 Pest management

149

150 The IPM treatment included a focus on growing healthy seedlings followed by weekly spray  
151 treatments with biological control agents as outlined in Table S1. Seedlings were planted in seed  
152 trays in coco peat derived from coconut husks (Jiffy DecoGro, Jiffy International AS, Norway) and  
153 were inoculated with *Trichoderma viride* (Royal University of Agriculture, Cambodia) at  $0.5 \text{ g L}^{-1}$  of  
154 coco peat and protected with insect exclusion nets ( $32 \text{ mesh inch}^{-2}$ ). After one week, seedlings  
155 were transplanted into the field and watered in with a *T. viride* solution. Thereafter, plants were  
156 treated weekly with three biocontrol agents: *Bacillus thuringiensis* subsp. *aizawa* (Ladda Co., Ltd.,

157 Thailand) at 0.4 kg ha<sup>-1</sup>, *Bacillus subtilis* (Tab Innovation Co., Ltd., Thailand) at 0.25 kg ha<sup>-1</sup>, and  
158 *Beauveria bassiana* (Tab Innovation Co., Ltd., Thailand) at 0.4 kg ha<sup>-1</sup>, which were mixed together  
159 and sprayed onto foliage weekly. During only the rainy season, farmers sprayed *Trichoderma*  
160 *harzianum* (Royal University of Agriculture, Cambodia) at 0.6 kg ha<sup>-1</sup> two times onto foliage in  
161 weeks four and five after transplanting seedlings. Orange essential oil (Prev-Am, ORO Agri Inc,  
162 USA), with the active ingredient sodium tetraborohydrate decahydrate, was also used periodically  
163 as an insecticide when needed. Conventional pesticides were used sparingly in the IPM treatment  
164 as follows: metalaxyl (Kalaxy 35WP, Papaya Trade Co., Cambodia) was sprayed one or two times as  
165 needed at a rate of 590 g ha<sup>-1</sup> for disease control during the rainy season, and imidacloprid  
166 (Confidor 200SL, Bayer, Germany) was sprayed once by each farmer at a rate of 667 ml ha<sup>-1</sup> during  
167 the dry season targeting thrips. Yellow sticky traps (35 x 40 cm) and two pheromone lures were  
168 also placed throughout each experimental field for monitoring.

169 Applying a farming systems research approach, plants cultivated under conventional  
170 management were grown according to the discretion of each individual farmer using pest  
171 management practices summarized in table S2 (Darnhofer et al., 2012; Dinakaran et al., 2013).  
172 Seedlings were typically grown in seed trays using field soil and without any netting protection.  
173 After transplanting, farmers used a wide range of different chemicals to control pests, which  
174 included eleven different insecticides and four different fungicides over the two seasons. Seedlings  
175 for no-spray control plots were grown with the same procedure used for IPM, but without using  
176 *Trichoderma viride*, and after transplanting they did not receive any pest management treatment.

177

178 *2.4 Data collection and analysis*

179

180 After transplanting seedlings into the field, we scouted all experimental fields each week  
 181 and selected five random plants per treatment on which we evaluated the damage by arthropod  
 182 pests and pathogens (Table 1). The pest and disease levels on each plant were scored on a simple  
 183 scale from 0 to 3, which was granularly calibrated so that it was meaningful and replicable for  
 184 farmers to differentiate: 0 nothing, 1 little damage/infestation, 2 moderate damage/infestation,  
 185 and 3 severe damage/infestation (Table S3). We also recorded yield, input costs (not including  
 186 labor), income from sales, and profit. Input costs included all the expenses for fertilizers,  
 187 conventional or IPM inputs, and gasoline for pumping water; input costs also included seed trays,  
 188 insect exclusion net, plastic mulch, drip irrigation system, and trellis system, adjusted for  
 189 depreciation. Yield related parameters, including marketable pod weight (kg) and price of  
 190 marketable pods per kg (USD), were collected by farmers and reported to researchers for each  
 191 treatment. Costs and benefits were calculated for each treatment by subtracting all the expenses  
 192 from all the income from selling marketable pods.

193

194 **Table 1.** Pests and diseases scored during surveys

195

Pest Category	Common Name	Scientific Name
Insect	Armyworm	<i>Spodoptera exigua</i> (Hübner) and <i>Spodoptera litura</i> (F.)
	Bean fly	<i>Ophiomyia phaseoli</i> (Tryon)
	Bean pod borer	<i>Maruca vitrata</i> (F.)
	Cowpea aphid	<i>Aphis craccivora</i> Koch
	Green stink bug	<i>Acrosternum hilare</i> Say
	Leafhopper	<i>Empoasca kerri</i> Singh-Pruthi

	Spider mite	<i>Tetranychus</i> spp.
	Sweet potato whitefly	<i>Bemisia tabaci</i> (G.)
	Thrips	<i>Megalurothrips usitatus</i> (Bagnall)
	Vegetable leaf miner	<i>Liriomyza sativae</i> Blanchard
Disease	Downy mildew	<i>Peronospora parasitica</i>
	Fusarium	<i>Fusarium oxysporum</i>
	Powdery mildew	<i>Sphaerotheca fuliginea</i>
	Pythium	<i>Pythium</i> spp.
	Rhizopus	<i>Rhizopus</i> spp. including <i>Rhizopus stolonifer</i> and <i>Rhizopus solani</i>
	Rust	<i>Uromyces vignae</i>
	Viruses	especially <i>Bean common mosaic virus</i>

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204

Due to very different growing conditions between the wet and dry seasons, all analyses were carried out separately for each season using R 3.5 (R Core Team, 2013). The global analyses of overall pest scores were performed by fitting a Generalized Linear Mixed-Effects Models (GLMM) using the treatment (IPM, conventional, and no-spray control) as a fixed effect, and pest, farm, and sampling week as random variables. Analyses of each pest's infestation scores were performed similarly but with pest removed as a random variable. Models were fitted using the *glmer* function under the *lme4* package (Bates et al., 2015) specifying a poisson error distribution and log link function. The effect of treatment was assessed using Type II Wald  $\chi^2$  from the package

205 *car* and function *Anova*, and the package *emmeans* was used to infer pairwise contrasts using  
206 Tukey's multiple comparison procedure. Pests for which at least one treatment did not have an  
207 average infestation score of at least 0.02 (i.e. at least one of 50 plants was scored as 1 or higher  
208 per week) were not statistically analyzed due to lack of data and model convergence issues. Data  
209 about yields, costs, incomes and profits were analyzed through a Linear Mixed-Effects model  
210 (LME) using the *lmer* function and specifying treatment as a fixed effect and farm as a random  
211 variable, and pairwise contrasts were inferred using Tukey's multiple comparison procedure, as  
212 described above.

213

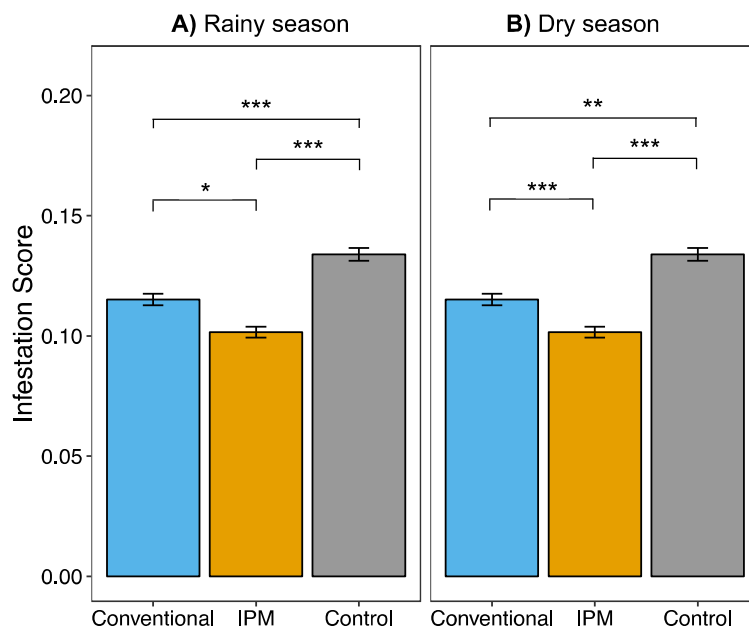
### 214 **3. Results**

215

#### 216 *3.1 Infestation*

217

218 A general view over the infestation scores of the entire dataset suggests differences  
219 between all the experimental treatments ( $\chi^2 = 61.8$ ;  $P < 0.001$  for rainy season, and  $\chi^2 = 45.1$ ;  $P$   
220  $< 0.001$  for dry season). Overall pest and disease infestation scores were higher in the conventional  
221 than the IPM management plots ( $P < 0.05$ ), while both strategies had lower overall infestation  
222 scores than the no-spray control plots ( $P < 0.05$ ) (Fig. 1).



223

224 **Fig 1.** Global infestation scores and standard errors for yard-long bean under conventional  
 225 management, IPM and no-spray control during both rainy (A) and dry (B) seasons. Significant  
 226 pairwise differences are denoted by asterisks (\*\*\*) =  $P < 0.001$ , \*\* =  $P < 0.01$ , \* =  $P < 0.05$ ).

227

228 A closer analysis of individual pathogens of yard-long bean indicated variability in the  
 229 severity of different diseases across the two seasons of study. In the rainy season, powdery  
 230 mildew and *Rhizopus* were the main pathogens, while rust was the main pathogen in the dry  
 231 season. *Fusarium* was not detected at all during the rainy season, while powdery mildew and  
 232 *Pythium* were detected at much lower levels in the dry season than in the rainy season. The  
 233 efficacy of management strategies also differed across the two seasons. Specifically, during the  
 234 rainy season, rust symptoms were reduced in IPM compared to conventional plots while powdery  
 235 mildew was lower in IPM compared to no-spray control plots but not compared to conventional  
 236 management. During the dry season, *Rhizopus* scores were lower under IPM than conventional  
 237 management, while symptoms of viruses were less in IPM compared to the no-spray control  
 238 treatment but not compared to conventional management. Downy mildew was not affected by

239 management and was detected at similarly low levels across both seasons of study. Pathogen  
240 scores for each season were never higher, on average, in the IPM treatment than the conventional  
241 treatment (Tab. 2).

242 The arthropod analysis revealed that aphids, armyworms, bean flies, and thrips were the  
243 most common pests with armyworms having higher scores in the dry season than the rainy  
244 season, while bean flies and thrips had higher scores in the rainy season than the dry season, and  
245 aphids reached similarly high levels in both seasons. The effect of pest management was  
246 consistent across both seasons against armyworms, with lower values under IPM than  
247 conventional management. It was also consistent across both seasons that aphids were controlled  
248 equally well by IPM and conventional management compared with the no-spray control. Damage  
249 by bean fly and leafhopper was controlled equally well by both IPM and conventional methods  
250 compared to no-spray control during the rainy season but these pests were detected much less in  
251 the dry season with no apparent management effects. Thrips were also equally controlled by both  
252 IPM and conventional methods during the dry season, but no effect of treatment was observed  
253 during the rainy season. There were no management effects on bean pod borer in either season  
254 and the pheromone lures did not appear attractive as no adult *M. vitrata* were captured. Spider  
255 mites were not observed in the wet season and stink bugs were not observed in the dry season.  
256 Leaf miner, and whitefly pest levels were very low in both seasons. Arthropod pest scores for each  
257 season were never higher, on average, in the IPM treatment than the conventional treatment  
258 (Tab. 3).

259

260 **Table 2.** Infestation scores for each pathogen recorded during both seasons. Different letters  
261 indicate significant pairwise differences between values in the same row within the same season  
262 at the  $P < 0.05$  level.

263

Pest	Rainy season					Dry season				
	$\chi^2$	P	Conventi onal	IPM	No-spray control	$\chi^2$	P	Convent ional	IPM	No- spray control
Downy mildew	4.5	0. 1	0.02±0	0.02± 0	0.01±0	1. 7	0.4	0.02±0	0.01±0	0.02±0. 01
Fusarium	N/ A <sup>1</sup>	N/ A	0	0	0	15 .4	<b>&lt;0.0 01</b>	0.038±0. 013 (b)	0.003±0 .002 (a)	0.013±0 .007 (ab)
Powdery mildew	8.8 6	<b>0. 01</b>	0.43±0.0 3 (ab)	0.41± 0.03 (a)	0.51±0.03 (b)	N/ A	N/A	0.008±0. 004	0.003±0 .002	0.003±0 .002
Pythium	0.7	0. 6	0.04±0.0 1	0.04± 0.01	0.03±0.01	N/ A	N/A	0.002±0. 002	0.002±0 .002	0.003±0 .002
Rhizopus	4.2	0. 1	0.34±0.0 2	0.28± 0.02	0.31±0.02	13 .1	<b>0.00 1</b>	0.04±0.0 1 (b)	0.01±0. 007 (a)	0.01±0. 01 (ab)
Rust	7.5 7	<b>0. 02</b>	0.09±0.0 1 (b)	0.06± 0.01 (a)	0.09±0.01 (b)	0. 4	0.8	0.56±0.0 3	0.53±0. 03	0.56±0. 03
Virus			ND <sup>2</sup>			10 .1	<b>0.00 6</b>	0.07±0.0 1 (ab)	0.05±0. 01 (a)	0.09±0. 02 (b)

264

265 <sup>1</sup> Statistical analyses were not applicable due to low infestation scores.

266 <sup>2</sup> Virus levels were not determined during the dry rainy season.

267

268

269 **Table 3.** Infestation scores for each pest recorded during both seasons. Different letters indicate

270 significant pairwise differences between values in the same row within the same season at the  $P <$

271 0.05 level.

272

Pest	Rainy season					Dry season				
	$\chi^2$	P	Convent ional	IPM	No-spray control	$\chi^2$	P	Conven tional	IPM	No- spray control
Aphids	42 .6	<0. 001	0.3±0.02 (a)	0.32±0. 02 (a)	0.48±0.02 (b)	26. 02	<0. 001	0.32±0. 02 (a)	0.27±0. 02 (a)	0.43±0. 02 (b)
Armywor ms	9. 06	0.0 1	0.1±0.01 (ab)	0.08±0. 01 (a)	0.13±0.01 (b)	20. 2	<0. 001	0.22±0. 02 (b)	0.16±0. 01 (a)	0.28±0. 02 (c)
Bean flies	11 .8	0.0 02	0.31±0.0 2 (a)	0.28±0. 02 (a)	0.38±0.02 (b)	N/ A <sup>1</sup>	N/A	0.017±0 .005	0.015± 0.005	0.015± 0.005
Bean pod borers	4. 1	0.1 2	0.11±0.0 1	0.11±0. 01	0.14±0.01	0.2	0.8	0.06±0. 01	0.05±0. 01	0.05±0. 01
Leaf miners	N/ A	N/A	0.004±0. 002	0.001± 0.001	0	1.6	0.4	0.02±0. 01	0.01±0	0.02±0. 01
Leafhopp ers	7. 52	0.0 2	0.08±0.0 1 (ab)	0.06±0. 01 (a)	0.1±0.01 (b)	2.3	0.3	0.05±0. 01	0.03±0. 01	0.04±0. 01
Spider	N/	N/A	0	0	0	0.7	0.6	0.09±0.	0.08±0.	0.09±0.

mites	A							01	012	01
Stink bugs	N/A	N/A	0.009±0.004	0	0.004±0.002	N/A	N/A	0	0	0
Thrips	4.7	0.09	0.18±0.01	0.16±0.01	0.21±0.01	11.2	<b>0.03</b>	0.07±0.01 (a)	0.05±0.01 (a)	0.09±0.02 (b)
Whiteflies	N/A	N/A	0.005±0.002	0.002±0.001	0.001±0.001	N/A	N/A	0.005±0.003	0.005±0.002	0

273

274 <sup>1</sup> Statistical analyses were not applicable due to low infestation scores.

275

276 *3.2 Productivity*

277

278 Yard-long bean production using conventional and IPM management strategies resulted in  
 279 statistically the same yields and subsequent incomes during both seasons of study (Tab. 4). In the  
 280 dry season, these yields and incomes were statistically higher than the no-spray control treatment  
 281 (but not during the rainy season). The costs of IPM practices were much higher than the  
 282 conventional treatments that farmers typically use and this resulted in significantly lower profits  
 283 for IPM management compared with the other treatments. In fact, during the dry season, the high  
 284 costs of IPM actually resulted in a net income loss.

285

286 **Table 4.** Yield, income, expenses and profit from yard-long bean cultivated under conventional,  
 287 IPM and no-spray control treatments during a rainy and dry season in Cambodia. Different letters  
 288 indicate significant pairwise differences between values within the same column at the  $P < 0.05$   
 289 level.

290

291

Season	Treatment	Yield (kg m <sup>-2</sup> )	Income (\$ m <sup>-2</sup> )	Expenses (\$ m <sup>-2</sup> )	Profit (\$ m <sup>-2</sup> )
Rainy	Conventional	1.68±0.1	0.5±0.03	0.34±0.003 (b)	0.16±0.03 (b)
	IPM	1.73±0.13	0.52±0.04	0.66±0.01 (c)	-0.14±0.04 (a)
	No-spray control	1.52±0.1	0.46±0.03	0.31±0 (a)	0.15±0.03 (b)
	F	3.5	3.6	1706.8	110.3
	<i>P</i>	0.05	0.05	<b>&lt;0.001</b>	<b>&lt;0.001</b>
Dry	Conventional	1.74±0.11 (b)	0.75±0.05 (b)	0.36±.003 (b)	0.39±0.05 (c)
	IPM	1.71±0.12 (b)	0.74±0.06 (b)	0.66±0.01 (c)	0.07±0.06 (a)
	No-spray control	1.33±0.12 (a)	0.58±0.06 (a)	0.31±0 (a)	0.27±0.06 (b)
	F	20.2	23.9	2597	64.1
	<i>P</i>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>

292

#### 293 4. Discussion and conclusions

294

295 The cultivation of yard-long bean in Cambodia represents an important source of income  
 296 for local farmers, and our results suggest that IPM practices can produce yields comparable to  
 297 conventional management practices. Global analyses across all insect pests and diseases indicate  
 298 that IPM controlled them better than farmers' conventional management practices. This result  
 299 supports previous IPM research on *Vigna unguiculata* that showed high performance of IPM  
 300 practices (Nabirye et al., 2003; Srinivasan et al. 2019). The success of our IPM package for yard-  
 301 long bean in Cambodia is especially important because pesticide imports have been increasing by  
 302 61% yearly, and banned or restricted chemicals are still widespread (Jensen et al., 2011;

303 Schreinemachers et al., 2017, 2015), which can have serious negative impacts on farmers' health  
304 (Kesavachandran et al., 2009; Krstevska-Konstantinova et al., 2001).

305         Depending on the season of study, disease pressures on yard-long bean and the efficacy of  
306 IPM and conventional management varied. During the rainy season, powdery mildew and  
307 *Rhizopus* spp. were the most serious diseases while rust was the most serious disease during the  
308 dry season (Schreinemachers et al., 2014). In all cases, the IPM controlled these diseases as well  
309 as conventional farmer practices. For powdery mildew in the rainy season, the IPM treatment  
310 controlled the disease significantly better than the no-spray control treatment. Powdery mildew  
311 has also been controlled in previous IPM studies by using cultural practices (Nathaniels et al.,  
312 2003; Oliva et al., 1999), and the same biological pesticides used in this study, including *T.*  
313 *harzianum* (Elad et al., 1998) and *B. subtilis* (Garcia-Gutierrez et al., 2013). Compared to the no-  
314 spray control, neither IPM nor conventional management better controlled *Rhizopus* spp. This is  
315 in contrast to previous studies in which *B. subtilis* induced disease resistance against *Rhizopus* spp.  
316 (Wang et al. 2013). Rust infestation was also high across all treatments during the dry season,  
317 despite similar expectations that *B. subtilis* treatments would induce resistance (Mishra et al.  
318 2018). In the future, seed priming with *B. subtilis* may enhance its effectiveness for combatting  
319 diseases (Mishra et al. 2018). Downy mildew, *Fusarium*, *Pythium*, and virus symptoms were all  
320 detected at very low infestation levels (< 0.1) and while our research did not show any significant  
321 differences among treatments for downy mildew or *Pythium*, previous research has highlighted  
322 the feasibility of using *Pseudomonas* spp. for biocontrol (Georgakopoulos et al., 2002), or to  
323 trigger plant systemic resistance (Monot et al., 2002).

324         Aphids, bean flies, and armyworms were the insect pests with the highest infestation  
325 scores in this study with aphids consistently present across both seasons, bean flies more  
326 abundant in the rainy season, and armyworms more abundant in the dry season. Each of these

327 pests was controlled at least as well by the IPM treatment as by farmers' conventional treatments.  
328 Aphid infestations were more severe in the no-spray control plots than in either IPM or  
329 conventional treatments during both seasons of study. *Beauveria bassiana* (Abdou et al., 2017)  
330 and orange essential oil (Mossa 2016) have both been found to be able to control aphids in  
331 previous studies. Controlling aphids may have also contributed to lower virus infestation during  
332 the rainy season in IPM compared to the no-spray control plots since aphids are important virus  
333 vectors (Damayanti et al., 2009). For bean flies, which were controlled significantly better by the  
334 IPM treatment than the no-spray control, recent research indicates that both the *Trichoderma*  
335 spp. and *B. bassiana* treatments may have been effective control strategies. *Trichoderma* spp.  
336 inoculation may stimulate the production of feeding deterrents (Mutune et al., 2016), while *B.*  
337 *bassiana* is directly entomopathogenic (Mascarin and Jaronski 2016). The armyworm was  
338 controlled better by the IPM treatment than the conventional treatment, which may be  
339 attributable to *B. thuringiensis* sprays, which can be highly toxic to early-instar lepidopteran larvae  
340 (Herrero et al. 2016). Leaf miners, spider mites, stink bugs and whitefly populations were  
341 controlled equally well across all treatments, with quite low infestation scores (< 0.10), and likely  
342 did not contribute much to yield loss.

343 Yields and income for our IPM treatment package were just as good as for conventional  
344 management with yields comparable to those obtained in commercial production systems (Coker  
345 et al., 2007). Unfortunately, IPM may come with higher costs than conventional pesticides,  
346 especially in countries where products for biocontrol are not widespread. These high input costs  
347 produced the gap in profitability between IPM and conventional management that we observed in  
348 this study. This gap could be reduced by decreasing the costs of inputs, the quantity of inputs,  
349 and/or by obtaining a premium for IPM produce. In many cases, IPM inputs are very difficult to  
350 obtain outside the research community in Cambodia and are only imported in small quantities at

351 high prices. Increasing demand for biopesticides has the potential to lower input costs (Glare et  
352 al. 2012). The amount of IPM inputs could also be reduced in a number of ways. The pheromone  
353 traps used to attract bean pod borer were not effective in the study region of Cambodia  
354 (Srinivasan et al. 2012), and can be dropped from an IPM package, which would reduce its price by  
355 about 20%. Fewer sprays of expensive biopesticides like *B. thuringiensis* may also be warranted.  
356 *B. thuringiensis* was sprayed weekly about six or seven times during each growing season and was  
357 the single most expensive IPM input accounting for nearly one third of IPM costs. Careful scouting  
358 for young bean pod borer larvae may be able to reduce this spray window and cut expenses.  
359 Furthermore, our IPM package includes multiple biocontrol agents with redundant protection  
360 against various insects and diseases. Research has shown that deploying multiple biocontrol  
361 agents simultaneously may actually have antagonistic effects and may not control target pests and  
362 diseases better than fewer products (Xu et al. 2011). Thus, removing relatively expensive  
363 biological control products such as the orange oil from the IPM package may not significantly  
364 reduce the overall efficacy of the management plan while reducing expenses. As an alternative to  
365 reducing the costs of an IPM package, creating market premiums for IPM produce could also  
366 increase the sales price of IPM produce and the profitability of using IPM packages (Ahuja et al.,  
367 2015).

368 The farming systems research approach employed in this study (Darnhofer et al., 2012;  
369 Norton et al., 1999) should be considered carefully when interpreting the results of this study. In  
370 our approach, farmers were responsible for spraying the plots, harvesting their beans, and  
371 reporting marketable yields. To minimize the likelihood that farmers accidentally sprayed no-  
372 spray control plots, we systematically located them on the outer edges of fields. Some insect  
373 pests, including some aphids (Nguyen and Nansen 2018), are known to be more abundant at the  
374 edges than centers of fields. Thus, the infestation rates in no-spray control plots may be biased by

375 them always being located along the edges of plots. Given the small size of no-spray control plots,  
376 it is also impossible to rule out possible effects of drift on the health of those plots over the course  
377 of the growing season. Spray drift may have decreased the pest and disease pressures in our  
378 small, no-spray control plots compared to if those plots had been larger. Farmers harvesting their  
379 own beans may also explain the relatively low infestation rates recorded for bean pod borers in  
380 this study compared to others in Southeast Asia (Yule and Srinivasan 2014; Srinivasan et al. 2019).  
381 While our researchers surveyed fields once per week, farmers harvested beans, including beans  
382 infested by bean pod borers, multiple times per week, which may have decreased the infestation  
383 rates apparent to researchers. Overall, while it is important to examine any systematic biases that  
384 can be introduced with a participatory, farming systems research approach, it is also important to  
385 acknowledge its benefits, which include: farmers gaining direct experience with IPM technologies,  
386 the ability to economically evaluate a relatively large number of field sites, and robust  
387 comparisons between IPM and conventional farmer practices.

388 In conclusion, our IPM package appears to be at least as efficacious as farmers'  
389 conventional pest management practices for controlling insect pests and diseases in yard-long  
390 bean in Cambodia, and potentially in other countries in Southeast Asia with similar growing  
391 conditions. We showed that our IPM strategy had a higher efficacy than conventional pesticides  
392 overall across all arthropod pests and pathogens. However, this did not appear to have a  
393 significant impact on yields as they were similar between conventional and IPM treatments over  
394 the two seasons of study. This research represents an important step in bringing new IPM  
395 technologies to the market and field in Cambodia, and future efforts should focus on trying to  
396 minimize IPM inputs, reduce IPM input costs, and develop markets for IPM produce in order to  
397 increase its profitability. It has been suggested that the dominance of pesticides in crop protection  
398 locked agriculture into a "pesticide trap", where the switch to other management techniques

399 represents an economic barrier (Wilson and Tisdell, 2001). Therefore, commitments by policy  
400 makers and stakeholder to promote IPM and reduce its costs are needed to unlock agriculture  
401 from conventional pesticides in Cambodia, similar to the successes achieved in Indonesia, Sweden,  
402 Norway, Denmark, Netherlands and Guatemala (Pimentel, 1997; Wilson and Tisdell, 2001).

403

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412

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