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Research article

Effect of climatic conditions and pest constraints on seasonal yield gaps in pesticide-free vegetable production under integrated pest management in Chiang Mai province, Thailand

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Abstract

Yield gaps of vegetables in integrated pest management (IPM) practice with no pesticide application are poorly documented in a tropical environment. This study investigated seasonal yield gaps under climatic and pest constraints on 0.36 ha of demonstration field of IPM-pesticide-free vegetable production at the Agricultural Resource System Research Station, Chiang Mai, Thailand. Seasonal yield gaps were quantified from yield records during October 2016 to June 2018. Comparisons of the yield gaps illustrated the seasonal variation of productivity and stability of vegetable yields. In winter seasons, vegetables were the most high-yielding in relation to national yield benchmarks. Most vegetable yields were suppressed during the dry and rainy seasons. Yields of cultivation of coriander and dill were maintained all year round. Risk analysis based on pathogenic and insect pest occurrences and severities were conducted with experienced field staff and by expert reassessment. Infestation of damping off, downy mildew, rust and mosaic viruses were notable in the production systems. Notable risks of insect pest damage were from infestations of aphid, thrip, flea beetle and fruit fly. The total annual income was USD 12,315.72. Mixed and relay cropping sustained overall monthly income in relation to the minimum income in March and May.

Introduction

The integrated pest management (IPM) approach, utilizing multiple measurements and techniques, aims to reduce pest populations below levels causing economic damage while taking into account impacts on the agro-ecosystem and human health (Vetek et al, 2017). Therefore, non-chemical treatments are the first option prior to chemical treatments in the IPM approach. In Thailand, IPM farmers adopted IPM to minimize pesticide application costs and their adverse exposure effects on human health (Timprasert et al., 2013). However, there has been little study regarding the economic context of applying IPM to vegetable production implemented by small farmers. Pesticide-free vegetable production requires intensive pest management in terms of time and labor with fluctuating yield levels (Rattanasuteerakul and Thapa, 2012). The price gap between pesticide-free and pesticide-grown vegetable products has not been remarkable in local markets (Chalermphol et al., 2013). Hence, understanding the associated consequences of weather conditions and the occurrence of pests and diseases on yield losses would support the adoption of seasonal adaptation techniques to maintain productivity all year round (Pereira et al., 2017).

Application of the yield gap concept as a means to understand biophysical opportunities led to closing the variations in cropping systems (Van Ittersum and Cassman, 2013). To illustrate yield limiting factors of vegetable crops on local farmland, yield gaps could be quantified from the crop cultivation dataset, including planting

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dates, crop nutrient uptakes, weed density and incidence of pests and diseases (Huat et al., 2013). Sadras et al. (2015) defined yield gap as the difference between two levels of yield involving economic, management and environmental constraints. The promising approach is to weight the actual yield with the benchmark which could achieve the highest or attainable yield of a particular crop in adjacent topographical conditions. Using yield gap estimations between the actual and attainable yields is a criterion for effectiveness of spatial and temporal management in crop production systems (Guilpart et al., 2017). Relative yields were used to compare the specific potential yield of certain system boundaries under different crops, cultivation practices and climatic conditions (Ponti, et al., 2012).

To illustrate pest risk, International Plant Protection Convention (2007) introduced Pest Risk Analysist (PRA), in which the risk of a pest was considered based on the combination of livelihood and impact on yield, namely Pest risk = Probability of introduction × Magnitude of impact. The implementation of the PRA was adapted into several aspects in different scales, for management option, yield loss, economic return and ecosystem service, which were specified case by case (European Food Safety Authority Panel on Plant Health, 2011). The current study adapted PRA to the plot production scale to quantify the risk of potential yield damage and the occurrence of pest infestation. The analytical process for PRA involved: 1) identification of the pest and the pathway, 2) risk categorization and assessment and 3) risk management to consider the option to reduce risk (US Department of Agriculture, 2012). The study aimed to demonstrate and compare seasonal yield gaps and to identify pest risks in IPM-pesticide-free vegetable production under local climatic conditions in Chiang Mai, Thailand.

Materials and Methods

Pesticide-free vegetable production system

The demonstration field (0.36 ha) of a pesticide-free vegetable production system has been in operation since 2014 at the Agricultural Resource System Research Station, Chiang Mai, Thailand (18º46'N, 98°55'E, 350 m above sea level). The soil is a loamy-skeletal, mixed, isohyperthermic Typic (Kandic) Paleustult, Mae Rim series. The annual average temperature was 26.8°C; the trend line for average monthly temperature is shown in Fig.1 . The daily average minimum and maximum temperatures were in the range 20.5–33.2°C and average total annual precipitation was 1,339 mm. The relative humidity dropped to 41–61% from February to April and remained at 75% from May to December (iWeatherStation, 2018). The accumulation of reference crop evapotranspiration (ET_0) based on Allen et al. (1998) reached 175.2 mm in March and dropped to 77.5 mm in December.

The demonstration field consisted of 100 subplots, each 1 m × 18 m. Relay cropping and IPM have been implemented since 2015. Four fulltime field staff took care of all steps from planting to harvesting the vegetable products according to the relay cropping schedule and practical measurement. A fixed sprinkler irrigation system provided an even distribution of water to minimize crop water stress throughout the year. A mixture of chicken manure and rice husks (1:1) was applied at 1 kg/m^2 to maintain the soil condition before each planting event. Chemical N:P:K fertilizers (16:16:16) were applied to leafy vegetables at 8.34 g/m^2 before planting and there were two applications of water-dissolved N:P:K (46:0:0) at 1.1 g/m^2 at 15 and 25 d after transplanting. For fruit vegetables, the 16:16:16 formula was applied three times at 13.88 g/m^2 before planting and at 10 g/plant at 30 and 40 d after transplanting; the water-dissolved 46:0: formula at 1.1 g/m^2 was applied at 15–20 d after transplanting. All pesticides, fungicides and herbicides were banned from the production system.

IPM measurement utilized yellow sticky traps set up every 4 m × 4 m and 14 yellow pan traps were set up within 0.16 ha along with hand-picking to control the fully range and growth stages of insect pests. Pest habitat and outbreaks were limited by the early harvest of pest-infested vegetables, manual weed clearing and ploughing the soil to expose it to sunlight and mulching plastic on soil heaps after harvest. The diversity of vegetable families was maintained in the relay cropping schedule. Cultivating similar vegetable families was avoided within subplots to buffer the pest and disease outbreaks. Diches were constructed in the demonstration field to help reduce the habitat of natural enemies such as frogs and dragonflies. Vegetable crops were classified according to differences in seasonal growth productivity and market demand. For example, a primary vegetable (PV) could be grown properly all year round (based on the experience of the agricultural technical officers) and satisfy high market demand, while a secondary vegetable (SV) could be grown properly only in the certain seasons. The SV group included indigenous vegetables which could be adapted for any seasons but had low market consumption.

The PV and SV groups of vegetables were cultivated rotationally in plots based on the relay cropping schedule. Therefore, vegetables were harvested in multiple plots every Wednesday and Saturday mornings. PVs had shorter harvest periods, such as 20–30 d for Chinese spinach and water convolvulus, 30–45 d for kale, pak choi and pai tsai, 45–60 d for bunching onion and 50–65 d for coriander. SVs had longer harvest periods, such as 60–90 d for cabbage, cauliflower and broccoli, 45–60 d for cucumber, 55–80 d for bush bean and yard long bean and 65–80 d for gourds. Fresh-cut yields were distributed to customers directly alongside the community market network (Limnirankul and Gypmantasiri, 2010) at the research station outlet on Saturday and at the Faculty's safe-food market on Wednesday.

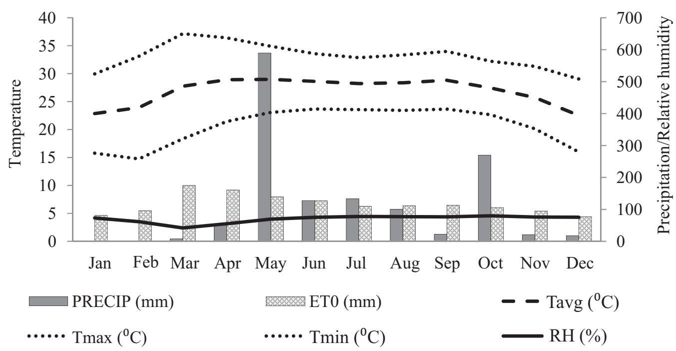

Fig 1. Climatic conditions at Agricultural Resource System Research Station in 2017 measured by field weather station (iWeatherstation, 2018, where PRECIP = precipitation, ET_0 = reference evapotranspiration, Tavg = average temperature, Tmax = maximum temperature, Tmin = minimum temperature and relative humidity

Data collection and evaluation of seasonal yield gaps

The seasonal yield gap was quantified based on the yield records of 11 primary and 27 secondary kinds of vegetable in seasonal periods in the tailored farm-plot database using the Microsoft Access software package from which data were extracted on multiple planting and harvest dates, the kinds of vegetables and the harvested fresh weights between October 2016 and June 2018. The plot number and harvest dates were used to generate a harvest ID. Yield records were sorted by fresh yield for each kind of vegetable in the dry, rainy and winter seasons. The yield records were classified regarding seasonal period based on the Meteorological Department of Thailand from 2015 to 2018, with the dry season commencing around 24 February to 3 March, the beginning of the rainy season was around 16 –22 May and the beginning of winter was around 22–30 October. The harvested yield of PVs was determine using the average fresh yield weight per square meter.

The relative yield (RY) was used to compare the fresh yield weight of 23 of the 38 vegetables from the different seasonal periods. The RYs of vegetables were computed based on the fresh yield divided by the benchmark yield. For Chinese cabbage and pak choi, the site average yields were used as benchmarks due to the lack of national average yields (Table 1). The national average yields from conventional practices were used as the benchmarks for the rest of vegetables. The national average yield was determined from data reporting crop production at the subdistrict level in 2015 and 2016 from the Information Technology and Communication Center, Department of Agriculture Extension, Thailand (Department of Agriculture, 2019). Income data were obtained in Thai baht and converted to US dollars (USD 1 = THB 29.97).

Seasonal pest risks were evaluated based on the field experience of the responsible staff for the production system. Semi-structured interviews were conducted with six experienced field staff, of whom, four had worked in vegetable production for 12 yr. Two agricultural technical officers responsible for field management identified and listed the pests that had occurred in the production system. The experts reviewed and reassessed the answers from the interviewees after the interviews. The occurrence and severity on yield loss of pests from pathogenic and insect causes were quantified from: low (1) to high occurrence (3) and from slightly damaged (1) to completely damaged fresh yield (5), respectively. The risk point was computed using the occurrence point multiplied by the severity point score of each pathogenic and insect cause in the different kinds of vegetable. The risk levels were grouped into four levels: ≤ 3, negligible; ≥ 3, notable risk; $R \geq 6$, medium risk; $R \geq 9$, high risk. In order to quantify the overview dynamics of income from the production system, vegetable sales records of PVs and SVs from the research station outlet were compiled and analyzed on a monthly basis from October 2016 to September 2019 and monthly primary and secondary vegetable incomes were determined from October 2016 to June 2018.

Statistical analysis

The data on the RYs of primary vegetables by seasons (Table 1) and the RYs of primary and secondary vegetables within each season (Fig. 2A 2B 2C) were analyzed using Analysis of variance and the Waller-Duncan test were used for mean comparisons with the significance level set at 0.05 and the type I/type II error seriousness ratio at 25. All statistical procedures were conducted using the IBM SPSS Statistics software, version 23.

Results and Discussion

Seasonal yield gaps

The PVs were cultivated on 54% of the total cultivated area with the SVs occupying the balance (Table 1). The yield gap study using national average yields as the benchmark revealed that the average RY ± SD of vegetables in the production system was 1.10 ± 0.64 (Table 1). The RYs of PVs were more than 1.0 in winter seasons in relation to the national benchmark yields (RYs > 1.0), except for leaf mustard. Water convolvulus had high productivity all year round. Thus, vegetable productivity in the northern regions benefited from higher net assimilation due to the longer day length, the higher range of diurnal temperature and higher heat unit accumulation at the higher latitude and elevations compared to the other regions of Thailand (Nath et al., 1999).

The vegetables with higher RYs indicated that the winter season was suitable for PVs, except for water convolvulus (Table 1). The seasonal weather constraints of yield gaps in the dry and rainy seasons were heat, rainfall and moisture which are all very high in tropical regions. High temperature conditions caused injury to the cell membrane leading to diffusion of electrolytes out of the cells (Levitt, 1980). In the leafy vegetables, an elevated temperature (32–36°C) increased stomatal conductance in vegetable leaves leading to reductions in the assimilation rate and fresh weight (Lai and He, 2016). The yield quantity and quality of lettuce and cauliflower reduced due to earlier maturity dates and delayed curd initiation with day temperatures above 28–30°C (Putland and Deuter, 2011).

The average day temperatures were only lower than 32°C in November, December and January. The average yields of Chinese spinach, leaf mustard, pak choi, Chinese cabbage and bunching onion were not different between the dry and rainy seasons. The relatively constant RYs of coriander and dill indicated that these two herbs could be grown and could maintain yield stability all year round (Table 1). The results of the conductivity testing for electrolyte leakage (Kuo et al., 1992) indicated that Chinese spinach and bunching onion were classified in the moderately tolerant group. In contrast, cabbage, yard long bean, eggplant, gourd and chrysanthemum were in the slightly tolerant group.

In dry seasons (Fig. 2A), productivities in relation to national yield benchmarks were not significantly different for most of the PVs. The leaf mustard RY was significantly the lowest, whereas water convolvulus was the significantly highest compared to the other vegetables. In rainy seasons (Fig. 2B), SV cultivation of eggplant and angel gourd produced more suitable yields than bitter gourd, okra and yard long bean. In the PV group, the yields for bunching onion, water convolvulus, Chinese spinach and Chinese cabbage were outstanding compared to the other vegetables. In winter seasons (Fig. 2C), spinach and chrysanthemum had high productivities compared to celery, bush bean, cucumber yard long bean and okra.

Considering the heat, rain and moisture constraints, the fresh weights of vegetables were highly correlated with the water application ratio of crop evapotranspiration (ET_c) and reference evapotranspiration

(ET_0) under the ET_0 application threshold (Nyathi et al., 2018). In a regional scale study, the precipitation-evapotranspiration index (the difference between precipitation and ET_0) had a negative correlation with brassica vegetables (Potop et al., 2012). Under the open field conditions with seasonal rainfall, the fresh weight of the leafy vegetables fluctuated under drought and water stress at 30–100% of ET_c (Maseko et al., 2019). The optimum relative humidity for pak choi growth was around 60% under a 35/28°C diurnal temperature regime (Han et al., 2019). Lower and higher relative humidities than the optimum reduced the net photosynthetic rate because of the relatively inefficient changes in stomatal conductance and the respiration rate. However, the lower diurnal temperature did affect the growth.

Table 1 Mean yield and relative yield (RY) of primary and secondary vegetables by season

Vegetable	Bench-mark yield‡ (kg/m²)	Season									Total n
		n	Dry Yield		n	Rainy Yield		n	Winter Yield		
			Mean (kg/m²)	RY		Mean (kg/m²)	RY		Mean kg/m²)	RY	
Kale†	0.92	6	0.71	0.68 b	14	0.67	0.63 b	40	1.15	1.01 a	60
Chinese spinach†	1.13	22	0.86	0.98 b	26	1.06	1.21 ab	17	1.33	1.52 a	65
Water convolvulus†	0.68	13	1.20	1.77 a	32	0.90	1.33 b	25	1.04	1.53 ab	70
Leaf mustard†	2.13	6	0.75	0.30 b	5	1.10	0.41 a	11	1.38	0.56 a	22
Pak choi†	0.84	12	0.58	0.78 b	10	0.86	1.02 ab	37	0.94	1.11 a	59
Chinese cabbage†	0.89 #	3	0.72	0.81 b	5	0.96	1.08 a	9	0.99	1.01 a	14
Pai Tsai†	0.52 #	–	–	–	4	0.54	0.68 b	13	0.83	1.09 a	17
Leaf lettuce†	0.73	5	0.39	0.69 b	3	0.42	0.74 b	17	0.96	1.70 a	25
Bunching onion†	1.06	3	0.74	0.70 b	4	1.77	1.67 a	14	1.44	1.36 a	21
Coriander†	1.00	8	0.92	0.91 a	5	0.81	0.81 a	14	1.11	1.11 a	27
Dill†	–	3	0.66	0.83 a	3	0.72	0.90 a	10	0.86	1.10 a	16
Carrot††	1.30	–	–	–	–	–	–	5	1.72	1.32	5
Cucumber††	3.18	–	–	–	–	–	–	4	1.56	0.75	4
Okra††	1.95	1	1.23	–	5	0.84	0.43	3	0.64	0.33	8
Cabbage††	2.50	–	–	–	–	–	–	2	1.39	–	2
Cauliflower††	1.42	–	–	–	–	–	–	2	1.61	–	2
Celery††	1.03	–	–	–	–	–	–	13	0.80	0.78	13
Chayote††	2.43	–	–	–	–	–	–	2	0.54	–	2
Zucchini††	–	–	–	–	–	–	–	2	2.08	–	2
Chrysanthemum††	0.50	–	–	–	–	–	–	8	1.03	2.05	8
Bush bean††	1.46	–	–	–	–	–	–	6	1.13	0.77	6
Yard long bean††	2.69	2	0.76	–	6	0.96	0.36	7	1.38	0.51	15
Wing bean††	1.32	–	–	–	2	0.87	–	–	–	–	2
Broccoli††	0.92	–	–	–	–	–	–	1	1.67	–	1
Angled gourd††	2.50	6	1.89	0.75	7	3.17	1.27	–	–	–	13
Snake gourd††	0.88	–	–	–	2	0.66	–	–	–	–	2
Sponge gourd††	–	–	–	–	–	–	–	3	0.90	–	3
Spinach††	0.38	–	–	–	–	–	–	8	1.00	2.64	8
Bitter gourd††	2.78	2	2.84	–	6	2.01	0.72	–	–	–	8
Pumpkin tip††	–	6	0.60	–	–	–	–	–	–	–	6
Eggplant††	2.49	–	–	–	4	5.04	2.02	–	–	–	4
Thai eggplant††	3.14	–	–	–	3	2.12	0.68	1	2.42	–	4
Cos lettuce††	–	–	–	–	4	0.80	–	5	1.27	–	9
Green oak lettuce††	–	–	–	–	–	–	–	4	1.38	–	4
Red oak lettuce††	–	–	–	–	–	–	–	5	0.80	–	5
Red sail lettuce††	–	–	–	–	5	0.68	–	3	1.19	–	8
Crisp head lettuce††	–	–	–	–	–	–	–	4	1.07	–	4
Malabar spinach††	–	–	–	–	4	1.74	–	4	1.50	–	4
Total		95			159			299			553

‡ Data report for crop production at subdistrict level in 2015 and 2016 from Information Technology and Communication Center, Department of Agriculture Extension, Thailand (Deparment of Agriculture, 2019)

† primary vegetable, mean values of relative yield superscript with different lowercase letters within each row denote significant ($p < 0.05$, type 1/type 2 error seriousness ratio = 10) differences between groups in different seasons.

††secondary vegetable, mean values of relative yield in different seasons were not tested in statistical procedures.

\# site averages used as benchmarks

Table 2 Occurrence and severity of pests and diseases in pesticide-free vegetable production system

Family	Vegetable	Pathogen	O*	S	R	Insect	O	S	R
Brassicaceae	Kale†	Downy mildew (W)	3	1	3	Flea beetle (D, W)	3	3	9
		Damping off (W)	2	1	2	Aphid (A)	2	3	6
						Cabbage shield bug (R)	1	1	1
	Pak choi†	Downy mildew (W)	2	1	2	Flea beetles (D, W)	1	2	2
		Damping off (W)	3	1	3	Aphid (A)	2	1	2
						Cabbage shield bug (R)	1	1	1
	Leaf mustard†	Downy mildew (W)	2	1	2	Flea beetle (D, W)	2	1	2
		Damping off (W)	3	1	3	Aphid (A)	3	1	3
						Leaf miner (W)	1	1	1
	Chinese cabbage†	Downy mildew (W)	3	1	3	Flea beetle (D, W)	3	1	3
		Damping off (W)	2	1	2	Aphid (A)	2	3	6
	Pai tsai†	Downy mildew (W)	2	1	2	Flea beetle (D, W)	3	1	3
		Damping off (W)	3	1	3	Aphid (A)	2	2	4
	Cabbage,	Downy mildew (W)	2	1	2	Flea beetle (W)	1	1	1
	Cauliflower,	Damping off (W)	3	1	3	Aphid (W)	3	1	3
	Broccoli	Soft rot (W)	1	1	1	Common cutworm (W)	1	3	3
						Cabbage plutella (W)	2	2	4
Cucurbitaceae	Cucumber	Downy mildew (A)	2	3	6	Cucurbit beetle (A)	3	1	3
						Aphids (A)	2	1	2
		Leaf blight (A)	1	1	1	Leaf eating caterpillar (A)	1	1	1
						Fruit fly (A)	2	2	4
	Angled gourd	Downy mildew (A)	2	3	6	Cucurbit beetles (A)	3	1	3
						Aphids (A)	1	1	1
		Leaf blight (A)	1	2	2	Leaf eating caterpillar (A)	1	1	1
						Fruit fly (A)	2	2	4
	Bitter gourd	Downy mildew (A)	1	2	2	Cucurbit beetle (A)	1	1	1
						Fruit fly (A)	3	2	6
		Leaf blight (A)	3	3	6	Leaf miner (A)	2	1	2
	Pumpkin tip	Mosaic virus (R)	3	2	6	Whitefly (R)	1	1	1
		Downy mildew (A)	1	1	1	Thrip (D)	2	1	2
						Aphid (A)	3	1	3
	Chayote	–	–	–	–	–	–	–	–
Fabaceae	Yard long bean,	Damping off (R)	3	1	3	Aphid (A)	3	2	6
	Common bean	Rust (W)	2	1	2	Pea pod borer (A)	2	1	2
						Fruit fly (A)	3	1	3
						Black bean bug (R)	1	3	3
Convolvulaceae	Water convolvulus†	White rust (R)	3	3	9	–	–	–	–
Amarylidaceae	Bunching onion†	Soft rot (R)	3	1	3	–	–	–	–
		Leaf blight (D)	2	1	2				
Apiaceae	Coriander†	Damping off	3	1	3	–	–	–	–
	Celery	Leaf blight (W)	2	2	4	–	–	–	–
		Damping off	3	1	3				
	Carrot	–				–	–	–	–
Solanaceae	Thai eggplant,	Damping off (W, D)	3	1	3	Aphid (R, W)	3	1	3
	Eggplant	Mosaic virus (D, R)	2	2	4	Thrip (D)	3	2	6
		Early blight	1	1	1	Whitefly (D)	2	1	2
						Eggplant fruit borer (R, W)	1	3	3
						Cotton bollworm (W)	1	1	1
Asteraceae	Grand rapid lettuce, Green oak lettuce, Red oak lettuce, Red sail lettuce	Damping off (W, D)	3	1	3	Common cutworm (seedling, A)	3	1	3
						Aphids (seedling, A)	2	1	2
Amaranthaceae	Chinese spinach†	–	–	–	–	Cabbage plutella (W, D)	3	1	3
Malvaceae	Okra	Mosaic virus (A)	3	3	9	Aphid (A)	3	1	3

† = primary vegetable; O = occurrence; S = severity; R = risk; W = winter; D = dry season; A = all year round

Occurrence scale: (1) low, (2) medium, (3) high occurrence.

Severity scale: (1) slightly damaged to (5) completely damaged fresh yield

Risk levels: ≤ 3 negligible, ≥ 3 notable risk, R ≥ 6 medium risk, R ≥ 9 high risk.

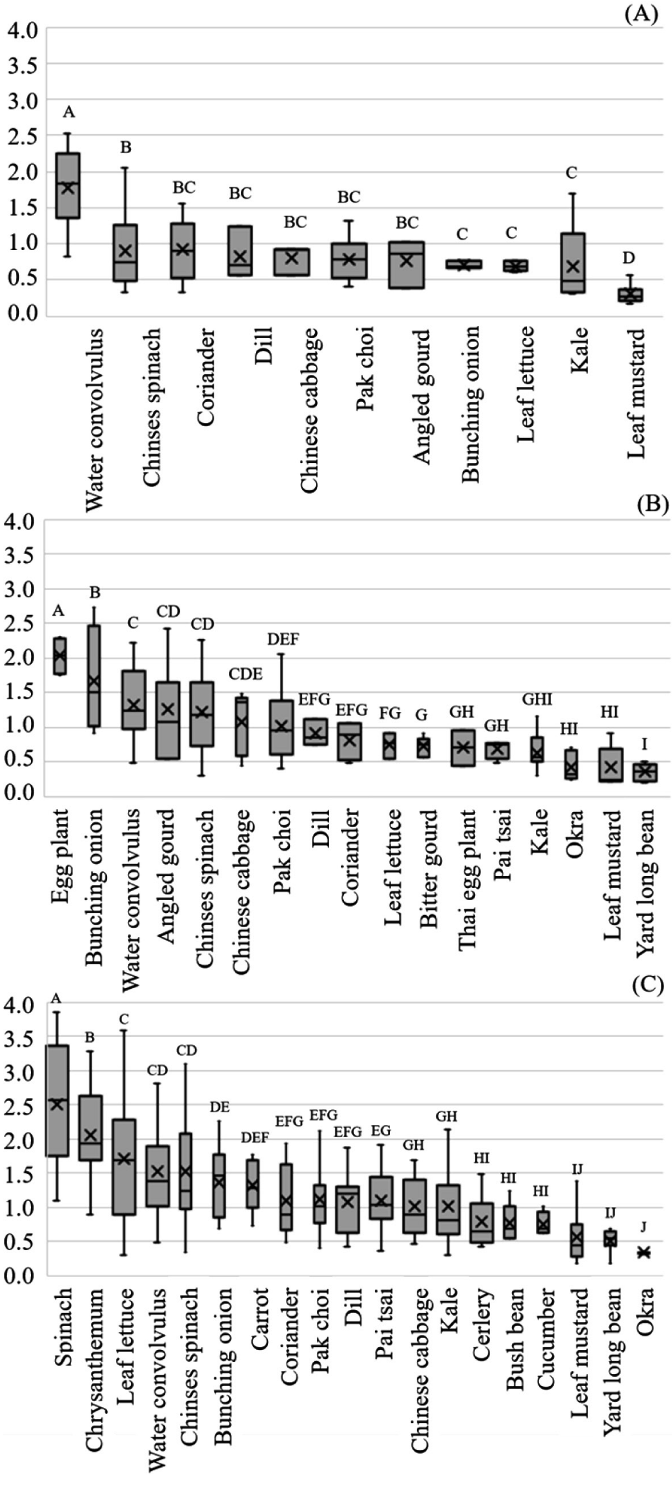

Fig 2. Relative yields in dry (A), rainy (B) and winter (C) seasons, where X = mean values with different uppercase letters indicating significant ($p < 0.05$, type I/type II error seriousness ratio = 25) differences within a season, horizontal lines in boxes = median values, boxes = ranges between first and third quartiles and vertical lines (whiskers) = ranges between maximum and minimum values

Seasonal pest risk

Vegetable production is severely susceptible to pests in the warmer temperatures and higher relative humidity of tropical regions (Ayyogari et al., 2014). High temperature conditions shorten the duration of the pathogenic life cycle and extend generation periods which can magnify populations and infestation in both the early and later growth stages of vegetables (Boonekamp, 2012). At the current study site, the risk of pathogenic pests degrading the fresh yields of most PVs was low ($R \leq 3$) and negligible, except for the high risk of white rust in the Convolvulaceae. There were coinciding risks ($R \leq 3$) of downy mildew and damping off on Brassicaceae vegetables in the winter seasons. Cucumber and angel gourd in the Cucubitaceae were vulnerable ($R \geq 6$) to downy mildew in all seasons, The signified risk ($R \geq 9$) was in water convolvulus, especially in the rainy season. High relative humidity produces favorable conditions for the outbreak of rust in the Convolvulaceae and Fabaceae (Upadhyay et al., 2017) and of damping off and downy mildew in the Brassicaceae and Cucubitaceae (Shephard and Wood, 1963; Saharan et al., 1997). The suitable temperature is around 15–25°C (Ghosh et al., 2015; Keinath et al., 2017; Sun et al., 2017). At the study site, the relative humidity reached 74% in June and peaked at 80% in October, with the average temperature around 23–26°C between November and February.

Virus infestations in the Cucurbitaceae, Solanaceae and Mavaceae occurred regularly because such outbreaks were associated with year-round infestation of sucking insects, including aphids, thrips and whiteflies (Roossinck, 2015). Aphid (*Aphis craccivora*) infested all year round on all vegetable families in the study site. Tropical aphid infestation is less specific to host plants (Peccoud et al., 2010). The development time was shortened and reproductive rate was more rapid when the temperature increased from 20°C to 35°C (Rao et al., 2018). Aphid risks were remarkable ($R \geq 6$) on kale, Chinese cabbage, yard long bean. The damages from aphid caused by sieve drain and virus transmission, especially, mosaic viruses (Dedryver et al., 2010) in the Cucurbitaceae, Solanaceae and Malvaceae. The flea beetle (*Phyllotreta chontanica*) infested the Brassicaceae in winter and dry seasons; in particular, the risk of flea beetle on kale was very high ($R \geq 9$). The Brassicaceae is in very specific host range of flea beetle, leafy feeding activity of flea beetle is more active when the weather become drier and warmer (Knodel, 2017). Thrip (*Scirtothrips dorsalia*) infestation was found on the Solanaceae in dry seasons. Thrips sucking individual cell sap causes tissue necrosis and a color change in the tissue from silvery to brown (Kumar et al., 2017). Thrip is the transmission vector for tobacco mosaic virus caused light and dark green mottled areas on the leaves and brown-frass scarring on the fruit skin (Kennelly, 2007). Fruit fly (*Bactrocera dorsalis*) infested the Cucurbitaceae in all seasons and was remarkable in bitter gourd ($R \geq 6$). The female fruit fly lay eggs under the fruit skin by using its ovipositor (Weems et al., 2019) and the fruit subsequently deteriorates because larvae feed on the pulp of fruit leads to other pathogens enter egg-laying holes (Deguine et al., 2015). In the current study there was no insect pest damages on the Convolvulaceae, Amarylidaceae and Apiaceae.

Monthly income

The total income summed from selling PV and SV products was USD 12,315.72 in a year (Fig. 3); overall, PV income accounted for 51.3% of the annual total income. The income reached 40,705–49,970 baht per month between December and March and dropped to 16,632 baht per month in April. Between June and November, the monthly incomes were slightly higher at 23,124–29,894 baht per month. The benefit of maintained diversity in the farming system was exemplified clearly when the PV income fell to 7,178 baht and the SV income to 12,136–18,983 baht in August, September and October. A review article noted that a hotter climate and higher humidity were significant constraining factors requiring training to help farmers to adopt diversified crop production as such factors were the causes of magnified pest risks (Lancaster and Torres, 2019). Intercropping and diversifying crop rotation could stabilize the overall yield level (Rosa-Schleich et al., 2019) because crop diversification can mitigate the adverse effects from pest outbreak and seasonal climate uncertainty. Diversified vegetables in a small farm system could overcome seasonal low outputs (Joshi et al., 2006) and reduce the risk of total crop failure compared to mono cropping (Altieri et al., 2009).

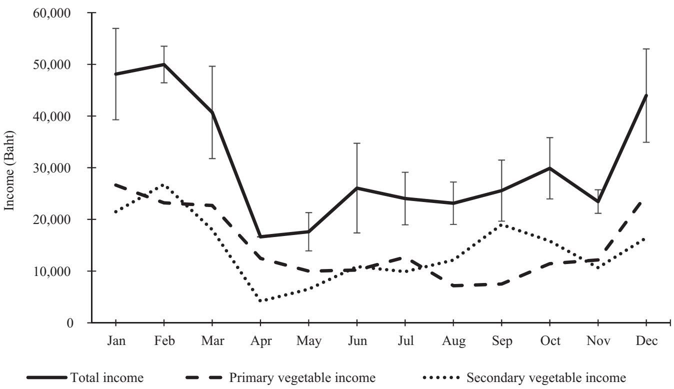

Fig 3. Monthly total income from October 2016 to September 2019 and monthly primary and secondary vegetable incomes from October 2016 to June 2018, where error bars indicate standard deviation and original income data provided in Thai baht converted using USD 1 = THB 29.97

Comparison of the seasonal yield gaps based on the relative yields of national yield benchmarks illustrated the impact of climatic constraints on extent of the gap in the vegetable yields among the dry, rainy and winter seasons in Chiang Mai province, Thailand. Such a comparison among the relative yields of growing different vegetables in certain seasons can guide the choice of which kinds of vegetables to grow based on planting those crops where fresh yield is less affected by the adverse effect of climate. A drop in the relative yield in the dry and rainy seasons can be considered as questioning cost effectiveness in the production system, with production inputs, including labor and fertilizer application, being reallocated to conform with the variation in seasonal relative yields. Pest infestation is unavoidable in a relay cropping schedule using IPM-pesticide-free vegetable production because vegetable family hosts exist in the system throughout the year. Occurrence and severity evaluation of pest infestation are necessary for farmers to make informed decisions on planting vegetables with a high seasonal pest risk. Pest risks should be considered through the evaluation process and could encourage the implementation of other management options, particularly, to introduce new vegetable crops into the production system. Seasonal yield gaps could be minimized by considering management options that consider evaluation based on relative yield and yield gap approaches. For example, micro-climate modification, including using shed nets and agricultural film for greenhouses, could reduce the effect of heat from infrared radiation on growing vegetables. The adoption of new vegetable crops, heat tolerant varieties and integration of indigenous vegetables might improve relative yields in the production system directly.

Conflict of Interest

All authors are employed full-time at the Faculty of Agriculture, Chiang Mai University.

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