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Hand pollination, not pesticides or fertilizers, increases cocoa yields and farmer income

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ABSTRACT

Increasing demand for cocoa and climate-related yield declines have sparked a multi-stakeholder debate on cocoa production strategies. Agrochemical inputs and pollination enhancement through hand pollination are two strategies to increase yields. Here, we test both strategies with field experiments in Indonesia. We show that even partial hand pollination (13% of easily accessible flowers/tree), and not fertilizers or insecticides, increases yield/tree by 51%. The more laborious 100% hand pollination of the entire tree increases yield/tree by 161%, and farmer's annual net income from 994 USD/ha up to 1,677 USD/ha, or 69% in the study area, after accounting for farm operational, hand pollination labor, and opportunity costs. Thus, intensifying cocoa pollination appears to be a potential solution for closing cocoa yield gaps and should be considered in the current industry-led discussion of designing farms for mitigation of climate change.

1. Introduction

The International Cocoa Organization (ICCO) forecasts that climate-related production challenges led to yield declines of 2.3% in the world cocoa production from 2017 to 2018 (ICCO, 2018a). Climate predictions suggest that by 2050, a 2 °C temperature increase would intensify current drought events and pest outbreaks, leading to further cocoa yield declines in major producer countries (Läderach et al., 2013; Schroth et al., 2017). In Indonesia, the third largest cocoa producer globally, shade tree removal tends to increase yields and immediate monetary benefits. However, this negatively affects the functional diversity of predators that can enhance farm resilience to pest outbreaks (Donald, 2004; Steffan-Dewenter et al., 2007; Clough et al., 2009). Yields and income of small scale farmers owning less than 2 ha of land continue to decline due to dwindling yields of cocoa trees beyond 25-30 years old. The volatile world market price for cocoa, abandonment of old unshaded cocoa farms, and migration to urban areas further add to the economic insecurity of smallholders (Donald, 2004; Hettig et al., 2017).

This so-called cocoa "boom-and-bust cycle" (Tscharntke et al., 2011) is addressed in the "Cocoa Action" efforts of the World Cocoa Foundation (WCF) trade group and other multi-stakeholder sustainability initiatives. Such initiatives primarily aim to both mitigate climate change impacts by preserving tropical rainforest, and to improve the livelihood of small-scale cocoa famers, which contribute 90% of the global cocoa production (Donald, 2004; Gockowski and Sonwa, 2011; Läderach et al., 2013; Schroth et al., 2017; WCF, 2018). While these sustainability initiatives promote sophisticated breeding technologies for climate-resistant varieties (MARS, 2018a) and improvements in fertilizer use (MARS, 2018b), they largely neglect alternative approaches such as enhancing pollination to improve cocoa yields sustainably (Young, 1982; Falque et al., 1995; Groeneveld et al., 2010; Wanger et al., 2014; Forbes and Northfield, 2017; Toledo-Hernández et al., 2017).

Cocoa is a cross-pollinated plant that highly depends on specialized insects for successful pollination (Entwistle, 1972; Young, 1986; Toledo-Hernández et al., 2017). Pollen limitation, as less that 10% of flowers in a tree are successfully pollinated in natural conditions, appears to be a major factor to improve yields in Indonesia (Groeneveld et al., 2010; Wanger et al., 2014; Toledo-Hernández et al., 2017). In experiments in

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Ivory Coast, increased pollen deposition rates on the style enhanced the number of seeds per fruit (Falque et al., 1995). Intensifying pollinator-flower visitation through landscape (e.g. forest conservation) and farm management (e.g. shade canopy cover) practices for improving pollinator habitats can increase pollination rates, pollen deposition, and improve fruit set (Young, 1982; Wanger et al., 2014; Forbes and Northfield, 2017; Toledo-Hernández et al., 2017).

However, no study so far has compared the performance of agrochemical intensification with pollination enhancement strategies in a realistic field experiment including landscape and farm management context, to identify the best approach for increasing cocoa yields. Further, studies linking hand pollination and economic performance of cocoa production strategies are lacking. Here, we use hand pollination and commonly applied fertilizers and insecticides to contrast the respective effects of pollination and chemical intensification on cocoa yield related variables (fruit set, harvested fruits and yields), and the pollination contribution for improving farmer income in Central Sulawesi, the major cocoa producing region of Indonesia (Witjaksono, 2016).

2. Materials and methods

2.1. Study site

The study area is located in the region of Napu Valley (S1° 27’ 48", E120° 21’ 6"), at the forest margins of Lore Lindu National Park, in Central Sulawesi, Indonesia (Fig. 1A) (Tscharntke et al., 2007, 2010). Lore Lindu National Park is one of the most important and

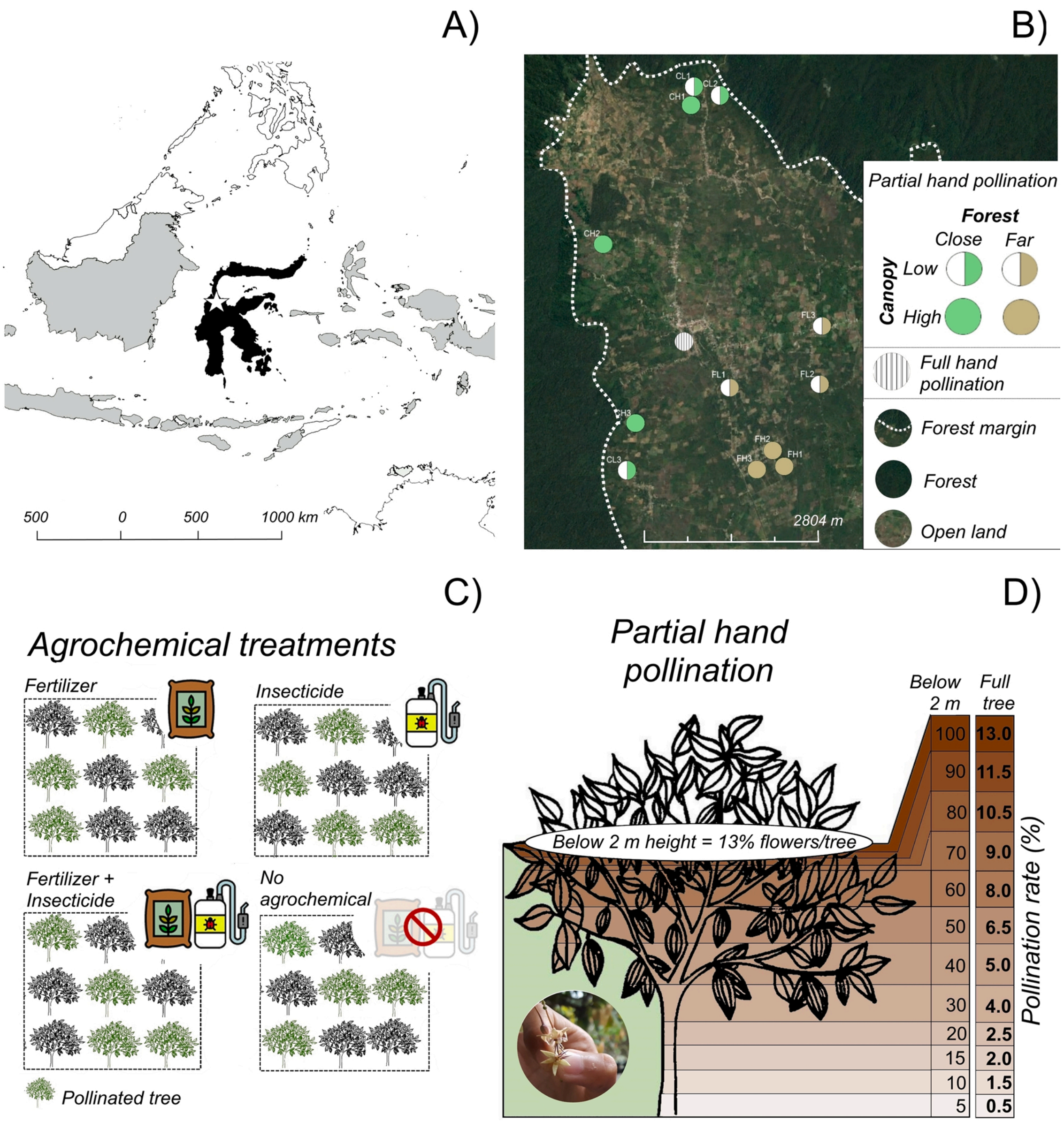

Fig. 1. The study area of the partial (13% flowers/tree) and full (100% flowers/tree) hand pollination experiment in the Napu Valley of Central Sulawesi, Indonesia (A). We selected 12 cocoa farms (plots) and sorted them into two landscape (close to forest = 0-800 m, far to forest = 1,500-3,400 m) and two farm management (low canopy cover = 0-15%, high canopy cover = 40-80%) categories, with three replicates for each category (B). In each plot, we established four agrochemical intensification treatments where we doubled the average amount of chemicals applied (double fertilizer, double insecticide, double fertilizer and insecticide, and no agrochemical application at all) (C). We randomly selected four cocoa trees from each treatment to be hand pollinated (green trees) plus one control tree/plot (natural pollination = 0% hand pollination rate) (C). Finally, we hand pollinated easily accessible flowers below 2 m height (corresponding to 13% flowers/tree) at 12 different rates ranging from 0.5 to 13% flowers/tree, with 16 tree replicates per hand pollination rate category (Electronic Appendix Figure S1) (D). In a separate farm (B, white dot), we conducted the full hand pollination experiment where we hand pollinated all flowers of eight cocoa trees (Electronic Appendix Figure S2).

well-preserved tropical forest remnants in Sulawesi and lies within the Wallacea bio-geographic region, a biodiversity hotspot. The Lore Lindu's more than 2,000 km^2 area is habitat to a large number of endangered flora and fauna, which are highly threatened by human action (Weber et al., 2007).

Cocoa farming is one of the major income-generating activities in the study region and Central Sulawesi, with 70% of Indonesia's cocoa production coming from this region (Witjaksono, 2016). This has led to immigration of people from other Indonesian islands seeking livelihood improvements through the cocoa cultivation sector. For instance, the cocoa expansion in the study area strongly contributed to increased household income, closing the poverty gap by over 18% between 2006 to 2013 (Hettig et al., 2017). However, increasing population density, cocoa demand, and subsequent land conversion to farmland has put high pressure on the remaining pristine tropical forest areas (Weber et al., 2007).

2.2. *Farm survey*

We conducted semi-structured surveys in 28 cocoa farms to characterize our study area and management practices. A summary of data collected in the farm survey is available in Electronic Appendix Table S1. Questionnaires included the cocoa tree varieties and age; amount and periodicity of fertilizer and insecticides use; and yields as dry cocoa beans weight. Further, we estimated the number of cocoa and shade trees/ha, and canopy cover as mean percentage in one ha farm using digital photographs and processing software Image J (Wanger et al. 2009; Maas et al., 2013). We calculated the farm distance to nearest forest margin in meters using satellite images and GPS coordinates.

2.3. *Experimental design*

We conducted two separate hand pollination experiments: 1) hand pollination of flowers below 2 m height (13% of all flowers/tree; hereafter "partial hand pollination"), and 2) hand pollination of all flowers on a tree (100% of the flowers/tree; hereafter "full hand pollination").

2.3.1. *Partial hand pollination*

This experiment aimed to calculate the effect of increased hand pollination of flowers, and landscape (forest distance) and farm management factors (agrochemical inputs, canopy cover) on yields (Electronic Appendix Figure S1). First, we selected 12 of the 28 surveyed farms (hereafter "plots") with a minimum distance of 200 m between each plot. The areas surrounding the plots consisted in average of 67% secondary forest combined with low and high shaded cocoa, and 33% vegetable gardens, settlements and open areas. We sorted the selected plots into four combined forest distance (close = 0-800 m, far = 1,500-3,400 m) and canopy cover (low = 0-20%, high = 40-80%) categories to evaluate the potential effect of forest distance and canopy cover on pollination and yields. Studies suggests that forest habitats and canopy cover provide suitable microclimatic conditions for pollinators, thus farms adjacent to forest and with high canopy cover may benefit from additional pollination (Clough et al., 2011; Tscharntke et al., 2011; Toledo-Hernández et al., 2017). Each category had three plot replicates: 1) close to forest and low canopy cover, 2) close to forest and high canopy cover, 3) far to forest and low canopy cover, and 4) far to forest and high canopy cover categories (Fig. 1B).

In each plot, we established four subplots of 10 m^2 area, separated by a minimum distance of 10 m for our agrochemical intensification treatments (Fig. 1C). In these subplots, we doubled the amounts of agrochemical inputs commonly used in the 28 surveyed farms (Electronic Appendix Table S1). Our four treatments were: 1) double fertilizer (Nitrogen, Phosphorus and Potassium or granule NPK = 373 [SE ± 82.8] kg/ha), 2) double insecticide (Capture® Concentrate = 3.4 [SE ± 1.1] l/ha), 3) double fertilizer (granule NPK = 373 [SE ± 82.8] kg/ha) and double insecticide (Capture® Concentrate = 3.4 [SE ± 1.1] l/ha), and 4) control where agrochemicals and fertilizer were not used (granule NPK = 0 kg/ha, Capture® Concentrate = 0 l/ha) (Fig. 1C). We followed the farmer periodicity of agrochemicals used for one harvesting season (six months), in which fertilizer is applied once (at the initial stage), and insecticide twice (at the initial stage and three months later). One month before starting the experiments farmers avoided application of any agrochemicals in the plots until the experiment ended.

In each subplot, we randomly selected four cocoa trees of the most common variety in the study area, which is a hybridization between the Forastero and Trinitario types (Bos et al., 2007a; Groeneveld et al., 2010) with no evidence of pest and disease attacks and of ages ranging from 5 to 19 years, thus, a total of 192 cocoa trees for the whole experiment. Following Groeneveld et al. (2010), we hand pollinated accessible flowers below 2 m height (or 13% of the flowers/tree) in 12 different rates, ranging from 0.5 ($\bar{X} = 14.4$ flowers/tree SE ± 3.0) to 13% ($\bar{X} = 231.3$ flowers/tree SE ± 28.0), thus comprising 16 cocoa trees for each rate category (Fig. 1D; Electronic Appendix Table S2). We additionally selected 12 cocoa trees as control (0% hand pollination; one for each plot) and monitored pollination success below 2 m height to contrast fruit development in our treatment trees with that under natural pollination.

2.3.2. *Full hand pollination*

To verify effects of the partial hand pollination experiment on the full-tree hand pollination on yields, we used a separate available plot of the close-to-forest distance category and with <10% canopy cover (Fig. 2A, Electronic Appendix Figure S1). In this plot, we randomly selected eight healthy cocoa trees. We clustered the selected trees in two age categories: four young (ca. 6 years old), and four old (ca. 36 years old). An average of 2,009 (SE ± 202.5) open flowers/tree were hand pollinated. We used the average tree yield recorded of all 28 farms to quantify the contribution of 100% hand pollination on yields in contrast to natural pollination in Napu Valley (Electronic Appendix Table S2).

2.4. *Hand pollination method*

We conducted the hand pollination of flowers daily for 60 days (from April to May 2017) following the labor effort of Groeneveld et al. (2010) and the method described by Falque et al. (1995). A detailed description on the hand pollination method is available in Electronic Appendix Figure S3. First, we removed all open flowers and fruits at any development stage from the tree one day before starting the experiments to promote tree resource allocation on flowering (Valle et al., 1990; Toledo-Hernández et al., 2017). On the next day, we pollinated each newly opened flower using three collected flowers from three different trees in farms not included in the experiments. This procedure aims to minimize potential tree self-incompatibility, and pollen grain deficits affecting pollination success. From the flowers collected, we carefully removed the flower petals to access the anthers containing the pollen grains. To perform the pollination, we rubbed the five anthers from each of the three flowers in the flower style of the flower pollinated. We removed flowers not hand pollinated below 2 m height to avoid natural pollination from unpollinated flowers, and to minimize the variability of resources between trees allocated to flower production.

2.5. *Fruit monitoring and harvesting*

We conducted the fruit monitoring (absolute number of fruit set, aborted, and fruit losses) and harvesting (absolute number of harvested fruits, and dry bean weight) of the hand pollinated flowers at a tree base (Electronic Appendix Figure S3). We monitored all hand-pollinated flowers three days after hand pollination to record number of fruit sets and number of early aborted fruits. Published evidence suggests that successful pollination, or fruit set, occurs within the first 48 h, while unpollinated flowers wilt and fall down from the tree after this time frame (Toledo-Hernández et al., 2017). We monitored un-aborted fruits

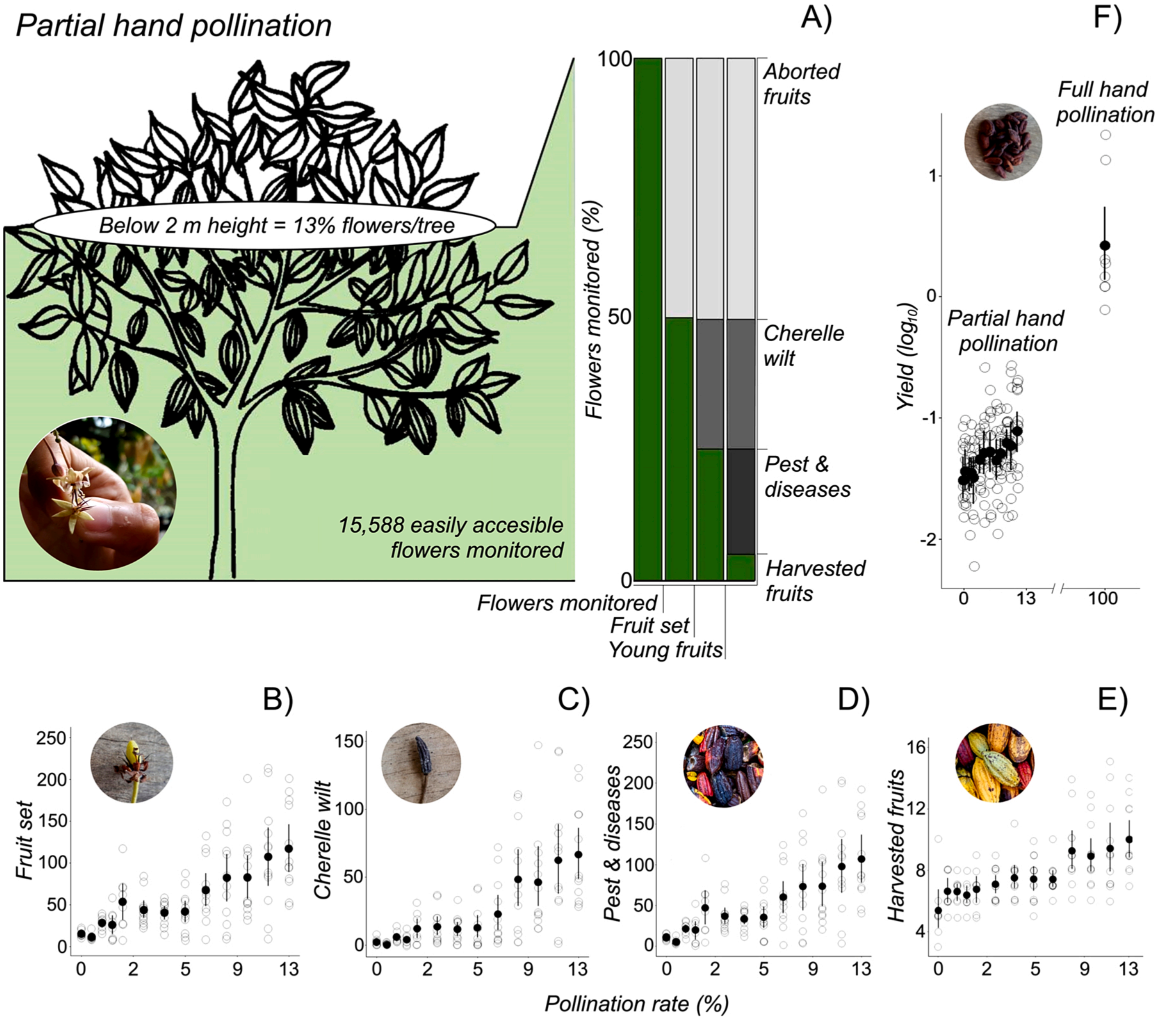

Fig. 2. The cocoa pollination-production cycle (A) and the positive effect of pollination intensification on fruit set (B), cherelle wilt (C), pest and diseases(D), harvested fruits (E), and the combined yield results from the partial (13% flowers/tree, solid line) and the full hand (100% flowers/tree, dotted line) pollination experiment (F). The cocoa pollination-production cycle starts with the fruit set of young flowers recorded 48 hours after pollen deposition on the flower style (A). In the partial hand pollination experiment, more than half of flowers dropped (A, Aborted flowers). Over one quarter of young fruits from non- aborted flowers naturally aborted after two weeks (A, Cherelle wilt). Pests and diseases occurring before the harvest contributed in further fruit losses (A, Pest & diseases). Finally, only 6.3% of pollinated flowers matured to harvestable fruits (A, Harvested fruits). The black dots in figures B to F indicate the means and vertical bars the standard error of the response variable.

daily for two weeks to estimate fruit development and number of cherelle wilted fruits. Cherelle wilt is a plant-regulated process, generally occurring within the first weeks of fruit development that causes fruits shrinking, darkening, and drying due to lack of nutrient resources to better sustain the remaining, non-wilted fruits (Wood and Lass, 2008). Further, we monitored fruits weekly until harvest to record incidences of the two most common cocoa pest and diseases in the study area: the mirid bug (*Helopeltis* sp.) pest and black pod (*Phytophthora* sp.) disease (Bos et al., 2007a). The harvest took place approximately six months after hand pollination started and lasted around three months (October-December 2017). We harvested and counted all fruits reaching maturity per tree from hand pollinated flowers. We fermented and dried the pooled seeds from healthy and diseased (fruits with signs of mirid bugs and black pod disease) fruits per tree following the regular practice by farmers to minimize income losses (Electronic Appendix Figure S4), and quantified dry bean weight per tree.

2.6. Statistical analysis

We analyzed only the data of the hand pollinated mature trees (age 10 to 19 years) from the partial hand pollination, because very young trees (age five to eight years) turned out to produce only very few fruits (Electronic Appendix Figure S5). This gave a total sample size of two (instead of three) plot replicates per landscape and per farm management categories and 128 (instead of 192) trees with eight to 12 (instead of 16) trees per each hand pollination category (Electronic Appendix Figure S1). We used model selection with a generalized linear mixed effects modelling approach (Burnham and Anderson, 2003) of the data with Poisson distribution pooled by tree. We quantified the effect (fixed effect variables) of (1) hand pollination (%), (2) forest distance (m), (3) canopy cover (%), and (4) agrochemical intensification treatments on the response variables (1) number of fruit set, (2) number of cherelle wilts, (3) number of pest and diseased, and (4) number harvested fruits, and (5) yield (kg dry bean weight). We included agrochemical intensification subplots nested in farm plots as random effect variables to estimate trees specific variations. All predictor and random effect variables were continuous, besides chemical intensification, which we treated as a categorical variable. We ran the models with negative-binomial distribution to correct for overdisperssion (Brooks et al., 2017), and scaled continuous predictors (i.e. count data = fruit set, cherelle wilt, pest & diseases, harvested fruits; proportion data = yield) to account for variables with different measuring scales

(Bolker et al., 2009, Bruce et al., 2020). Then, as several models satisfied the ΔAICc ≤ 2 cut-off criterion for best-fit models (Anderson, 2007), we averaged the coefficient of the best fitting models (Electronic Appendix Table S3). Finally, we conducted a least square means analysis for a multiple comparison to quantify the effect of our agrochemical intensification treatments on each of the response variables (Electronic Appendix Table S4) (Lenth and Lenth, 2018).

2.7. *Hand pollination and farmer income*

To understand the economic implications of pollination for cocoa farmers and household livelihood, we calculated the overall effect of pollination intensification on income, or pollination-related net income ($I_{Pollnet}$), by extrapolating yield increase from our full hand pollination experiment across farms in Napu Valley (Electronic Appendix Table S5). We calculated the $I_{Pollnet}$ per hectare in four steps: (1) I_{Gross}= Gross income, (2) *OC*= Operational costs, (3) *HP*= Hand pollination effort, and (4) *OP*= Opportunity costs using data from our 28 farm surveys in 2017.

2.7.1. *Gross income (I_{Gross})*

We defined the I_{Gross} as the monetary value of the farmer's harvested cocoa dry beans (yield). This was calculated as the product of yield increase compared to the control trees (Y_{Δ}= kg dry beans/ha) and the marketable price of cocoa or *CP* (Electronic Appendix Table S6).

$$I_{Gross} = Y_{\Delta} * CP$$

2.7.2. *Operational costs (OC)*

The *OC* are the economic investments of a farmer to run operation of the farm and include purchase of agrochemical and organic inputs (fertilizers, herbicides, insecticides) and labor for farm management (e.g. tree pruning, weeding, agrochemical/organic input application, harvesting, processing).

$$OC = \sum \text{inputs} + \text{labor}$$

Based on information of inputs (69.9 USD/ha, SE ± 19.3) and labor (26.3 USD/ha SE ± 5.5) costs from our farm survey, we know that in 2017 the *OC* = 96.2 (SE ± 24.8) USD/ha (Electronic Appendix Table S1). The calculated labor value is the annual mean expense recorded in the farm surveys. It accounts for a seven to eight-day worker salary supporting in farm management activities at 3.7 USD/day (8-9 hours) rate.

2.7.3. *Hand pollination effort (HP)*

The *HP* is the product of the pollinated days multiplied by the investment for hand pollination one ha farm area (*PI*).

$$HP = N \text{ day(s) pollination} * PI$$

We recorded from the hand pollination trainings prior our study (Electronic Appendix Figure S3) that a worker can fully (100% flower/tree) hand pollinate 77 trees (one tree in ~7 minutes, without collecting any flower and fruit development data) in one working day. This means a *PI* of 39 (SE ± 3.7) USD/day at a worker salary of 3.7 USD/day in 2017. Thus, we assumed that 10-11 workers will be required to full hand pollinate 813.5 (SE ± 389) trees/ha (from farmer surveys) in one day (eight to nine-hour work). As we pollinated flowers daily for 60 days in the hand pollination experiment, the *HP* costs were 2,342.4 (SE ± 219.2) USD/ha. However, successful pollination can be assumed to occur every second day (30 working days), because flowers are receptive to pollen for even more than 48 hours after opening (Toledo-Hernández et al., 2017). This reduces *HP* cost to 1,171.2 (SE ± 109.6) USD/ha.

2.7.4. *Opportunity costs (OP)*

The *OP* accounts for income that a household member may receive if working in other activities outside the farm (hand pollination) (Buchanan, 1991). To account for *OP*, we assumed a 100% hired labor for pollination, thus the *OP* was one (100% = 1). As in our study area, the salaries are equal regardless the local labor activity carried out, this makes *HP* and *OP* identical.

$$OP = 1$$

2.7.5. *The pollination-related net income ($I_{Pollnet}$)*

Finally, $I_{Pollnet}$ is the earnings a farmer obtains after subtracting the *OC, HP and OP* from the I_{Gross}.

$$I_{Pollnet} = (I_{Gross} – OC) – (HP * OP)$$

2.8. *The $I_{Pollnet}$ scenarios justification*

To understand the possible variations on the potential benefits of hand pollination on farmers' income in Napu Valley, we developed three pollination-related net income increase scenarios accounting for two *HP* (daily and every second day for 60 days) and three *OC* (high, average and low *OC)*. We summarized the results of the income scenarios in Electronic Appendix Table S5.

2.8.1. *Conservative*

We assume the same hand pollination labor as in our experimental study and the highest (maximum value) farm operation costs reported in our survey (*HP* daily for 60 days and high *OC*).

$$I_{Pollnet} = (I_{Gross} – 378.8 \text{ USD/ha}) – (2{,}342.4 \text{ USD/ha} * 1)$$

2.8.2. *Realistic*

We assume half of the pollination labor as in our experimental study and the average farm operation costs reported in our surveys (*HP* every second day for 60 days and high *OC*).

$$I_{Pollnet} = (I_{Gross} – 96.2 \text{ USD/ha}) – (1{,}171.2 \text{ USD/ha} * 1)$$

2.8.3. *Optimistic*

We assume half of the hand pollination labor as in our experimental study and the lowest (minimum value) farm operational costs (*HP* every second day for 60 days and lowest *OC*).

$$I_{Pollnet} = (I_{Gross} – 1.8 \text{ USD/ha}) – (1{,}171.2 \text{ USD/ha} * 1)$$

3. Results and discussion

3.1. *Partial hand pollination effects on yield related variables*

In our partial hand pollination experiment, we analyzed 128 cocoa trees pollinated up to 2 m above the ground (13% of all flowers/tree) for 60 days and found that pollination and not agrochemical intensification increased all cocoa yield related variables (Table 1, Fig. 2). Similar to Groeneveld et al. (2010), partial hand pollination of 13% flowers/tree increased dry bean weight of the hand pollinated flowers by 51.3% per tree ($p < 0.0001$; Table 1 E, Fig. 2F) compared to natural pollinated (0% hand pollination, i.e. control) trees.

Our multiple comparison analysis shows that hand pollination in our control treatments provides similar fruit set, cherelle wilt, pest and disease load, harvested fruits, and yields compared to both, fertilizer and insecticide addition, as well as their combination (Electronic Appendix Table S4). The results of the fertilizer treatment on yield can be associated to the nature of Central Sulawesi soils, which are considered very fertile with soil nitrogen stock of 9,900 kg/ha (Dechert et al., 2005; Groeneveld et al., 2010), suggesting no nutrient limitations in our study area. Furthermore, the evolution of resistance of pests to insecticides (Entwistle, 1972; Asogwa and Dongo, 2009), and its little targeted applications, affecting also beneficial pest predators (Croft and Brown,

Table 1
The generalized linear mixed effect model results of the agrochemical intensification and partial hand pollination (13% flowers/tree) experiment in cocoa trees of Central Sulawesi, Indonesia. We investigated the response of amount of (A) fruit set, (B) amount of cherelle wilt, (C) pest and disease (number infested fruits), (D) number harvested fruits, and (E) yield (dry bean weight g/tree) to agrochemical intensification treatments (double fertilizer [Fertilizer], double fertilizer and double insecticide [Fertilizer + Insecticide], and double insecticide [Insecticide]) and farm parameters Forest distance (m) and Canopy cover (%). Significant *p-values* highlighted in bold.

		Coefficient	SE	Adjusted SE	*z-value*	*P-value*
A	**Fruit set**					
	Intercept	3.904	0.103	0.104	37.421	**<0.0001**
	Hand pollination	0.494	0.030	0.031	16.009	**<0.0001**
	Forest distance	0.071	0.090	0.091	0.779	0.436
	Canopy cover	−0.184	0.083	0.084	2.191	**0.028**
	Fertilizer	0.087	0.175	0.177	0.490	0.624
	Insecticide	0.259	0.175	0.177	1.465	0.143
	Fertilizer + Insecticide	0.173	0.175	0.177	0.979	0.328
B	**Cherelle wilt**					
	Intercept	2.685	0.257	0.260	10.327	**<0.0001**
	Hand pollination	0.488	0.047	0.047	10.331	**<0.0001**
	Forest distance	0.167	0.250	0.252	0.662	0.508
	Canopy cover	−0.263	0.242	0.245	1.073	0.283
	Fertilizer	0.075	0.303	0.306	0.246	0.805
	Insecticide	0.294	0.303	0.306	0.963	0.335
	Fertilizer + Insecticide	−0.074	0.304	0.307	0.242	0.809
C	**Pest and diseases**					
	Intercept	3.718	0.112	0.113	32.907	**<0.0001**
	Hand pollination	0.553	0.033	0.033	16.703	**<0.0001**
	Forest distance	0.096	0.100	0.101	0.951	0.342
	Canopy cover	−0.208	0.093	0.094	2.200	**0.028**
	Fertilizer	0.093	0.213	0.215	0.430	0.667
	Insecticide	0.271	0.213	0.215	1.261	0.207
	Fertilizer + Insecticide	0.157	0.213	0.215	0.731	0.465
D	**Harvested fruits**					
	Intercept	2.057	0.036	0.037	55.732	**<0.0001**
	Hand pollination	0.144	0.031	0.032	4.539	**<0.0001**
	Forest distance	−0.059	0.033	0.033	1.767	0.077
	Canopy cover	−0.010	0.031	0.032	0.316	0.752
	Fertilizer	−0.012	0.091	0.091	0.135	0.893
	Insecticide	0.082	0.088	0.089	0.919	0.358
	Fertilizer + Insecticide	0.067	0.089	0.090	0.747	0.455
E	**Yield**					
	Intercept	5.607	0.052	0.053	105.668	**<0.0001**
	Hand pollination	0.095	0.015	0.015	6.338	**<0.0001**
	Forest distance	−0.064	0.044	0.044	1.463	0.143
	Canopy cover	−0.023	0.046	0.047	0.487	0.626
	Fertilizer	−0.008	0.073	0.074	0.108	0.914
	Insecticide	0.027	0.073	0.074	0.361	0.718
	Fertilizer + Insecticide	0.127	0.073	0.074	1.708	0.088

1975, Syarief et al., 2017), may be the major reason for the neutral or even negative effects of spraying insecticides on pest and diseases.

In contrast to naturally pollinated trees, fruit set of the partial (13% flowers/tree) hand pollinated trees increased more than seven times ($p < 0.0001$; Table 1A, Fig. 2B) and the amount of harvested cocoa fruits increased by 85.1% ($p < 0.0001$; Table 1D, Fig. 2E), despite a 30 times increase in early fruit abortion or cherelle wilt ($p < 0.0001$; Table 1B, Fig. 2C), and 10 times higher fruit losses to pest and diseases ($p < 0.0001$; Table 1C, Fig. 2D). The premature fruit abortion, i.e. the cherelle wilt (Falque et al., 1995), allows the cocoa tree to allocate energy towards the development of remaining fruits and, hence, may explain the increase in fruit set and fruits.

At the landscape level we found that forest distance did not affect any yield related variables (Table 1). This may be due to the ecology and behavior of tiny cocoa pollinators (Ceratopogonidae and other small insects); single flights cover only a few meters (Chumacero de Schawe et al., 2013) and, hence, forest to farm movement for flower foraging may be limited. At the farm level, canopy cover had a negative effect on fruit set ($p = 0.028$; Table 1A) and led to lower pest and diseases infestation ($p < 0.028$; Table 1C). This highlights the trade-offs of agroforestry systems (Clough et al., 2011; Tscharntke et al., 2011; Blaser et al., 2018). For instance, shade trees may compete with cocoa for nutrients (Isaac et al., 2007), but may also enhance predators and predation of herbivores (Maas et al., 2013).

3.2. *The cocoa fruit development*

In the partial hand pollination experiment, we recorded a fruit set of 50.8% ($N = 7,920$ flowers) of all 15,588 hand pollinated flowers examined, while only 6.3% ($N = 1,015$ flowers) developed harvestable fruits (Fig. 2A, Electronic Appendix Table S2). Fruit set in the control trees, where flowers were naturally pollinated ($N = 1,177$ flowers examined), was of 10.3% ($N = 121$ flowers), and only 3.6% ($N = 43$ flowers) reached maturity and were harvested. In the full hand pollination experiment, fruit set was of 47.5% ($N = 7,635$ flowers) of the 16,072 flowers examined, while only 2.7% ($N = 428$ flowers) developed to harvestable fruits (Electronic Appendix Table S2). The increased fruit set after hand pollination, and the general low levels of harvestable fruits are in accordance with previous studies in Central Sulawesi (Bos et al., 2007b; Groeneveld et al., 2010).

We found overall fruit losses before the harvest of 87.5% ($N = 6,929$) in the partial hand pollination experiment, and of 67.8% ($N = 82$) in the control trees. In the full hand pollination experiment, we recorded fruits losses of 94.4% ($N = 7,202$) before the harvest. The overall fruit losses in our hand pollination experiments are similar to published results of hand pollination studies in Indonesia (72% to 92%) (Bos et al. 2007a; Groeneveld et al., 2010) and Brazil (79%) (Hasenstein and Zavada, 2001), but higher than in the Ivory Coast (29%) (Falque et al., 1995). The main reasons for cocoa fruit losses before the harvest are internal

Table 2
The summary results of the partial (13% flowers/tree), and full (100% flowers/tree) hand pollination experiments on cocoa yields at the tree level ($Y_{\Delta/tree}$), and yield extrapolations at the farm level ($Y_{\Delta/ha}$) (A), and the results of the pollination-related income increase ($I_{Pollnet}$) scenarios (B). The hand pollination of cocoa increases yields by 51.3% in the partial, and 161.5% in the full hand pollination experiment (A). The result extrapolations of a 161.5% yield increase at the farm level ($Y_{\Delta/ha}$) as recorded in our full hand pollination experiment (A) translates into farmer income benefits after accounting for hand pollination costs in the realistic and optimistic scenarios, but not in the conservative scenario (detailed calculations of the $I_{Pollnet}$ are available in Electronic Appendix Table S5).

A. Hand pollination experiments

	Partial hand pollination			**Full hand pollination**		
$Y_{\Delta/tree}$ (kg/tree)[1]	*Value*	*SE*	*% Change*	*Value*	*SE*	*% Change*
No pollination	0.228	0.023	0.0	0.660	0.061	0.0
Pollination	0.345	0.031	51.3	1.726	0.359	161.5
$Y_{\Delta/ha}$ *extrapolations* (kg/ha)[2]						
No pollination	185.5	18.7	0.0	536.9	49.6	0.0
Pollination	280.6	25.2	51.3	1,404.1	292.0	161.5

B. Pollination-related income increase ($I_{pollnet}$) (USD/ha)

Scenario[3]	*Description*	*Value*	*SE*	*% Change*
No pollination	Natural pollination	993.7	100.7	0.0
Conservative	*HP* daily for 60 days + high *OC*	129.1	592.8	-.87.0
Realistic	*HP* every second day for 60 days + medium *OC*	1,582.9	592.8	59.3
Optimistic	*HP* every second day for 60 days + low *OC*	1,677	592.8	68.8

[1] Cocoa yield results of the partial and full hand pollination experiments at the tree level (kg/tree).

[2] Yield increase extrapolation of the partial and full hand pollination experiments to the farm level (kg/ha) considering 813.5 (SE ± 389) tree/ha from the 28 farm surveys (Electronic Appendix Table S1).

[3] The I_{Pollnet} scenarios assume the costs of two hand pollination effort (*HP*), and maximum (high), average (average), and minimum (low) operational costs (*OC*) recorded in the 28 farms surveys (Electronic Appendix Table S1).

factors such as early fruit abortion or cherelle wilt within the first two weeks after pollination, while external factors such as pest and diseases occur throughout the fruit development (Falque et al., 1995; Bos et al., 2007a; Toledo-Hernández et al., 2017).

In the partial hand pollination experiment, we observed an early fruit abortion (cherelle wilt) of 45.1% ($N = 3{,}584$) of the successfully hand pollinated flowers, and of 14.9% ($N = 18$) in the control trees. In the full hand pollination experiment, the 70% ($N = 5{,}347$) of all flowers developing into fruits were early aborted. The cocoa mirid bug (*Helopeltis* sp.) and the black pod disease (*Phytophthora* sp.) caused fruit losses before the harvest of 77.1% ($N = 3{,}345$) in the remaining 4,336 un-aborted fruits in the partial hand pollination, while pest and diseases caused 62.1% ($N = 64$) fruit losses of the remaining 103 un-aborted fruits in the control trees. In the 2,288 un-aborted fruits of the full hand pollination experiment, the 81.3% ($N = 1{,}860$) of fruits were lost by the mirid bugs and black pod disease. Our high incidence of pest and diseases and their contribution to fruit losses was higher than the 23% previously reported in hand pollination experiments in Central Sulawesi (Bos et al., 2007a). Signs of cocoa mirid bugs were found on 74.5% ($N = 756$) and 55.8% ($N = 24$) of the 1,015, and 43 harvested fruits of the partial hand-pollinated and control trees, respectively. We found black pod disease on 23.3% ($N = 236$) and 28% ($N = 12$) of the harvested fruits, and only 2.3% ($N = 23$) and 16.3% ($N = 7$) were not affected by any pest or disease. The 56.8% ($N = 243$) and 22.4% ($N = 12$) of the 428 harvested fruits in the full hand pollination experiment showed incidence of pest and disease, while 20.8% ($N = 89$) presented no signs of mirid bugs and black pod.

3.3. *The economic benefit of hand pollination in Napu Valley*

Our partial (13% flowers/tree) and full (100% flowers/tree) hand pollination experiment led to a yield increase per tree of 51.3% or 0.117 (SE ± 0.008) kg/tree and of 161.5% or 1.066 (SE ± 0.298) kg/tree, respectively (Table 2A). Extrapolating our yield results in both hand pollination experiments to farm level using data from 28 farms across our study site, considering an average of 813.5 trees/ha (SE ± 76.1) from our 28 farms surveyed, translates to a farm yield increase from 185.5 (SE ± 18.7) kg/ha to 280.6 (SE ± 25.2) kg/ha, and from 536.9 (SE ± 49.6) kg/ha to 1,404.4 (SE ± 292) kg/ha in the partial hand and full hand pollination experiment, respectively.

The extrapolation of a 161.5% yield increase from the full (100% flowers/tree) hand pollination experiment and calculation of the three different pollination-related net income increase ($I_{Pollnet}$) scenarios (Table 2 B, Electronic Appendix Table S5), shows that the realistic ($I_{Pollnet} = 1{,}582.1$ USD/ha, 59.3% change) and optimistic ($I_{Pollnet} = 1{,}677$ USD/ha, 68.8% change) scenarios provide favorable income returns. In contrast, the conservative scenario shows negative income returns ($I_{Pollnet} = 129.1$ USD/ha, -87.3% change) because of the assumption of an overly high labor investment. Overall, these results suggest that a realistic cost calculation (including current farmer operational, and opportunity costs, and hand pollination labor) of hand pollinating all flowers on a cocoa tree can be highly profitable for farmers in Napu Valley.

3.4. *Hand pollination and cocoa sustainability*

In general, our results are in line with previous studies in our study area suggesting that pollen rather than resource limitation is a major factor determining yields (Bos et al., 2007b; Groeneveld et al., 2010). These findings may provide guidance to develop diversified farming strategies that include pollination to improve yields and farmer's income.

However, we consider three main aspects requiring attention in order to elucidate the full potential of cocoa hand pollination for promoting sustainability in cocoa. First, our study was carried out for one harvesting season, limiting our understanding on the effect of hand pollination on tree resources and long term yield stability. For instance, cocoa trees under intensive hand pollination may allocate resources to sustain highly energy demanding fruits (Bos et al., 2007b), leading to a resource depletion and abnormal flowering and fruit abortion (Valle et al., 1990). Furthermore, tree aging, a major issue in most of the growing regions in the world where trees are over 25 years, may reduce the effectiveness of hand pollination for improving yields (Wessel and Quist-Wessel, 2015). Hence, we suggest that future research should focus on long-term yield stability over several harvesting seasons under hand pollination and on tree physiology parameters that can influence hand pollination effectiveness.

Second, the high labor costs of hand pollination, as we observe in the conservative scenario, may blur the economic benefit to farmers. Future studies should determine the best labor cost-benefit hand pollination rate (e.g. from 20% to 40% of all flowers). We need also more detailed analyses of the pollination labor efforts (to identify hand pollination minimum time interval and time-saving, skilled applications of hand pollination) to reach maximum attainable yields. In addition, the quantification of hand pollination effects on global cocoa yields and farmer income in major producer countries will help to understand the true potential of hand pollination strategies for sustainable production.

Lastly, Natural pollination is a sustainable and inexpensive alternative to hand pollination, but the effects of different farm management strategies on pollinators at the farm (e.g. shade tree and soil litter management) and landscape level (e.g. forest conservation), as well as cocoa pollinator identity and their potential breeding sites are little understood (Young, 1982; Frimpong et al., 2011; Forbes and Northfield, 2017; Toledo-Hernández et al., 2017). Multi-stakeholder initiatives such as 'Deforestation Free Cocoa' (UNFCCC, 2018) and 'International Cocoa Initiative' (Cocoa Initiative, 2018), which focus on ecological farming approaches, will help to leverage the full pollination potential in practice.

4. Conclusions

In this large-scale study we show that hand pollination can increase cocoa yields by 51.3% with partial hand pollination of 13% of flowers, and by 161.5% with full hand pollination of all flowers, resulting in an annual farmer income by up to 68.8%, independent of fertilizer and insecticide inputs. In the near future, research studies should give priority to understand the long term sustainability of hand pollination, and to develop alternative methods and tools to optimize procedures and to reduce pollination labor, thereby increasing income benefits. Our results suggest that cocoa pollination deserves a more prominent position in cocoa research and stakeholder discussions to sustainably meet the global cocoa demand increases of 2.5 to 3% annually (ICCO, 2018b), secure farmers' livelihoods, and to end deforestation in a time of global climate change.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2020.107160.

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